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SIMULATION OF BULK MINING AT DEPTH WITH BACKFILL IN ONTARIO MINES

Final Report - Volume 4

NUMERICAL MODEL CALIBRATION STUDIES

by

Mines Research Department
INCO Limited

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MICROMEDIA

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ABSTRACT

This is the final report on the numerical model calibration studies portion of the Ontario Division of Inco Ltd. project entitled, "SIMULATION OF BULK MINING AT DEPTH WITH BACKFILL" which was partially funded under the Department of Supplies and Services contract file number 14Q.23440-6-9033. The objective of the project is to create and calibrate a three dimensional elasto-plastic numerical modelling program for use by the Canadian mining industry. The original project duration was four years which has been extended by six months to allow the orderly completion of the numerical code calibration with the field monitoring data.

The following report presents the numerical modelling work conducted as part of this study which compares the output from several different codes to the field monitoring data collected from one specific mining site over a four and one half period. The limitations of the different codes is discussed and their performance to the MINE3D code compared.

SOMMAIRE

Ce rapport traite des études de calibration du modèle numérique réalisées dans le cadre du projet intitulé "Simulation de minage en vrac de gisements à grande profondeur avec utilisation de remblai". Le projet, réalisé à le division Ontarienne d'Inco Ltée, a été payé en partie par le département des services et équipements (numéro de contrat 14Q.23440-6-9033). L'objectif de ce projet est de créer et de calibrer un programme de modèlisation numérique élasto-plastique tri-dimensionnel à l'usage de l'industrie minière Canadienne. La durée du projet, initialement le quatre ans, a été prolongée de 6 mois pour permettre l'achèvement de la calibration numérique du logiciel avec les mesures de pressions prises sur le terrain.

Dans ce document on présente le travail de modèlisation numérique effectué dans le cadre de cette étude. L'étude compare les résultats de différents programmes informatiques appliqués aux mesures expérimentales provenant de même site minier sur une période de quartre ans et demi. Les limites des différents programmes sont discutées et leur performances sont comparées à celle du programme MINE3D.

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1.0 INTRODUCTION

This is the final report on the calibration of the numerical modelling codes created as part of the project entitled "Simulation of Bulk Mining at Depth With Backfill in Ontario Mines ". The aim of the project, which was jointly funded by Inco Limited and the Canadian and Ontario Governments under the Mineral Development Agreement (MDA), was to create a three-dimensional elasto-plastic boundary element numerical modelling program that can be used by the Canadian mining industry to simulate mining at depth. There are two components to this four year project: the development of the numerical code, and the collection of field monitoring data to be used in the code calibration.

1.1 Purpose of the Numerical Modelling Calibration Studies

The purpose of this numerical code calibration study is to attempt to simulate the rock mass response to bulk mining that was measured in the field monitoring portion of this project (Volume 3: Field Monitoring Program). The results of this study are intended to show both the ability of the different codes used to accurately simulate the rock mass response but also to show their limitations in doing so.

The five different numerical codes utilized in this study were used to simulate the mining of 4500 vertical retreat (VRM) mining block. This area was heavily monitored, while it was mined over a 4½ year period, to determine stress changes, rock mass displacements and location of stress relaxation zones around openings as mining progressed. The stress relaxation zones are areas where the rock mass had actually failed or where the mining geometry created stress shadows in areas that had not failed but were no longer in a state of high stress. A detailed explanation of the data collected and the subsequent analysis is given in the Volume 3 report.

1.2 Discussion of the Numerical Modelling Studies

A series of calibration modelling for the 6600-6700 ore block has been conducted using various available numerical modelling programs. The numerical codes used for the calibrations are discussed in the following sections.

1.2.1 BEM3D

BEM3D is based on the indirect boundary element method. Uniform distributions of forces or displacement discontinuities are applied on each planer surface element. Details of this formulation are given by Wiles and Curran (1982).

The three-dimensional elastic model employs planar, quadrilateral shaped surface elements which are positioned in three-dimensional space to form a continuous envelope around each excavation. In the boundary element analysis, forces are applied on these elements such that the surface normal and shear stresses are reduced to zero from their initial field stress values. This accommodates opening interaction and results in the redirection of applied field loads around excavations, through pillars and abutments. A complete three-dimensional geometrically accurate analysis can be conducted with this technique.

1.2.2 FLAC

The numerical code, FLAC, is a two-dimensional finite difference program which is developed and distributed by the Itasca Consulting Group in Minnesota USA. Information pertaining to the formulation of the FLAC code as well as its usage is outlined within the FLAC User's Manual, Itasca Consulting Group Inc. (1986).

FLAC has been chosen for the calibration modelling for three reasons. Firstly, the program is readily available to the Mines Research Group at Inco for use in numerical modelling. Secondly, the program is well-supported by the Itasca Consulting Group. Because Itasca is experienced with both the writing and the use of the FLAC code, they are able to provide professional assessment of the models being run of the case study site. Their assessment and assistance aids in ensuring accuracy with the FLAC calibration modelling. Thirdly, and most importantly, the FLAC program was utilized because of its capability of simulating plastic and/or elastic behaviour of the modelling medium. The determination of the areas within the rock mass which have undergone failure is a vital aspect of the calibration modelling.

1.2.3 MINE2D

The MINE2D program has been developed in-house at Inco as part of the COMDA contract. The program is two-dimensional and utilizes the boundary element formulation. As with the FLAC code, the MINE2D program is able to model the elasto-visco-plastic behaviour of the medium as well as simulating multiple materials. The MINE2D code also has the ability of simulating the interaction of fault/slip movement. For further detail on this program refer to Volume 5: MINE2D User's Manual.

1.2.4 3DEC

3DEC is a three-dimensional distinct element program developed and distributed by Itasca Consulting Group, Inc. The formulation of 3DEC is described by Cundall (1988), Hart et. al. (1988), and Itasca (1991).

The 3DEC program is primarily intended to simulate the behaviour of a jointed rock mass, and the code explicitly models the response of rock joints. 3DEC can also be used to simulate the elastic/plastic behaviour of a three-dimensional continuum.

In reference to the case study site, the model region is divided into a system of tetrahedral finite-difference zones and the influence of joint behaviour is ignored. 3DEC is then equivalent to a three-dimensional version of FLAC.

1.2.5 MINE3D

MINE3D is a three-dimensional boundary element program developed specifically for this COMDA project. The program has two distinct features: 1) -it simulates localized regions of plastic yield within an elastic continuum; and 2) -multiple regions containing different materials can be defined to simulate backfill within ore bodies. The formulation of MINE3D is given in Volume 2, and the user's manual is given in Volume 6.

2.0 CREIGHTON MINE FIELD MONITORING SITE

To help the reader follow the approach used in the calibration of the different numerical codes to the field monitoring data it is necessary to provide some background on the monitoring site and program which was a major part of this project. What follows is a summary of the monitoring site initial and changing geometry and the mining methods used to create this geometry. The properties of the materials that made up the site and the natural field stress conditions that governed their behaviour are also defined.

The field monitoring program was conducted at INCO Limited's Creighton Mine situated in the south-western section of the Sudbury Basin in Northern Ontario, Figure 2-1. For a complete description of the field monitoring site, refer to Volume 3 "Field Monitoring Program".

2.1 The Mining Method and Mining Geometry

The field monitoring site at Creighton Mine is situated in the 400 Ore Body which is located between 6600 and 6800 level and 7000 and 7200 level, as shown in Figure 2-2. The copper-nickel sulphide ore body at this depth (2035 to 2215 meters below surface) strikes east-west and dips at 70 degrees to the north. The ore body is approximately 200 meters in length (along strike) and 100 meters wide. The host rock, on the hangingwall, is primarily norite while the footwall consists of a mixture of granite and gabbro.

2.1.1 VRM Mining Method

The majority of ore at Creighton Mine has been recovered using a bulk vertical retreat method (VRM). The ore zone areas within the mine are divided into mining blocks. These blocks are excavated panel-by-panel using the primary VRM mining method. Normally, the panels are square (in plan section) with dimensions of 13 metres by 13 meters. The vertical height of the panels generally ranges from 25 to 76 meters.

The VRM mining method requires a top sill and a bottom sill to be developed in the ore body above and below the mining area, respectively. Each VRM panel is drilled off using 165 mm diameter holes and approximately 3 meters of burden. In any given VRM panel, the ore is broken-up by lowering explosives down the holes and progressively crater-blasting from the bottom sill upward. The vertical height of each progressive blast varies from 1.5 to 3 metres and this blasting of the lifts is completed when a 10 to 13 metre crown remains. For the recovery of the remaining ore in the VRM panel, all of the holes in the crown pillar are loaded with explosives and detonated in a single blast.

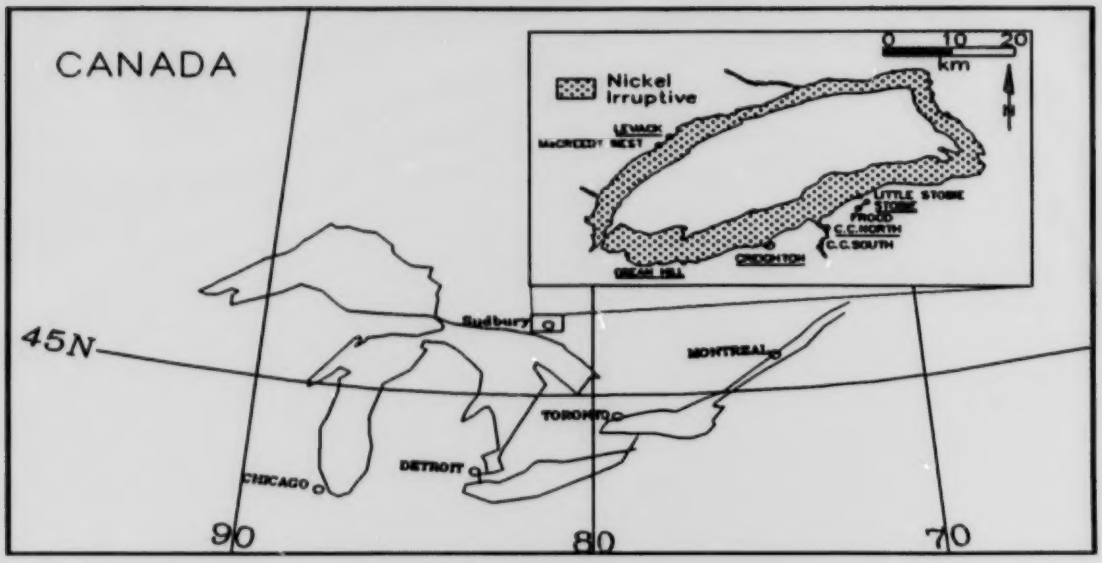

Figure 2-1 Location of INCO's Creighton Mine, Sudbury Basin Map

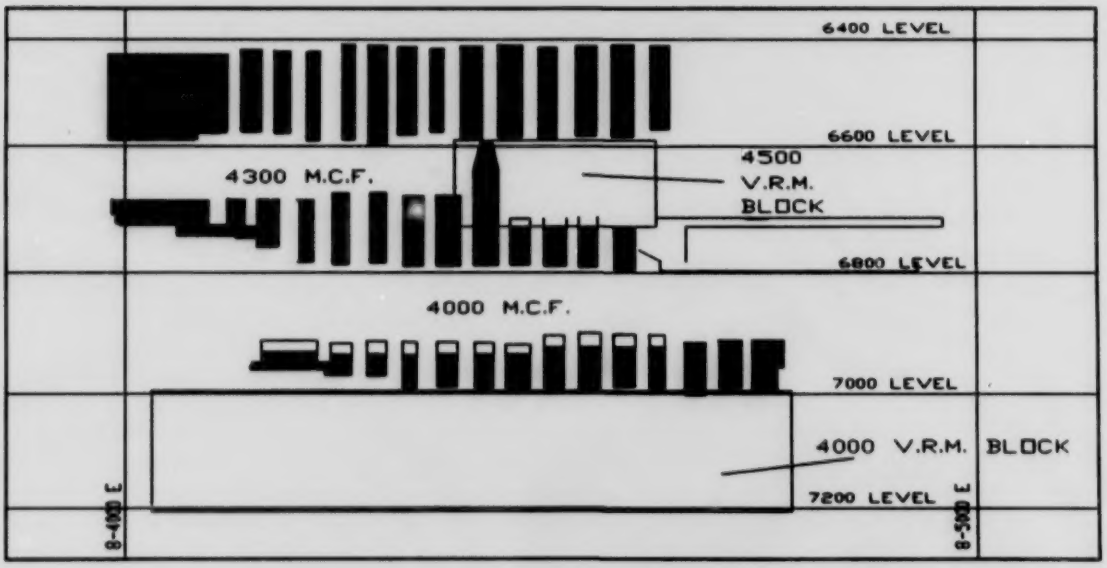

Figure 2-2 Creighton Mine, Field Monitoring Site: 400 Ore Body
(LONGITUDINAL SECTION)

After each of the blasts, the ore is removed from the VRM panel with a scoop tram on the bottom sill level. The removal of this broken ore creates a large void within the panel for the next day's production. The scoop tram conveys the ore away from the bottom of the panel where it is dumped into a chute. From the chute, the ore is transported to the mine shaft and subsequently it is skipped to surface.

When all of the ore has been mined from a VRM panel, the stope void is backfilled using a cemented hydraulic fill. The backfilling of a panel is completed prior to the mining of any adjacent VRM panel.

2.1.2 The Field Monitoring Site Geometry

The main portion of the field monitoring was concentrated in 4500 VRM mining block between 6600 level and 6700 level. The level plans of these two mining horizons are shown in Figure 2-3 and Figure 2-4.

4500 block was mined for six cuts above 6800 level using a mechanized cut and fill (MCF) mining method; it was then converted to the VRM method to remove the remaining ore (the remaining ore block being 83 meters by 83 meters by 53 meters high). As part of the mining method conversion, a destress slot 7 meters wide by 53 meters high was mined from hangingwall to footwall on the west side of the block as shown in Figures 2-2, 2-3 and 2-4.

The concept behind the creation of the destress slot, which separates 4500 VRM block from 4300 MCF block, is to reduce the horizontal stress. At the 6650 level, the magnitude of the major principal stress is high (σ_1=96 MPa); this stress is oriented horizontally along the strike of the orebody. The slot creates stress relaxation zones which, in turn, allow the VRM mining in the 4500 block to progress within stress shadows. This, thereby, decreases the potential of having to drill in highly stressed ground and also allows the progressive mining to passively transfer the high stress zone to the abutments of the mining area.

The mining blocks above 4500 VRM block have been completely mined out up to 6000 level using the MCF method. Only the rib pillars remain, which will not be recovered until well after the end of the monitoring program.

The ore between 6300 level and 7000 level (refer to Figure 2-2) was initially mined using the MCF method. This mining area was later converted over to the vertical retreat method after the monitoring program had begun. The detailed timing of the mining method conversion is outlined in Volume 3, Field Monitoring Program. Approximately 40 meters of ore separates 6800 level from the mining below; there was no mining in this ore block while the destress slot was being removed.

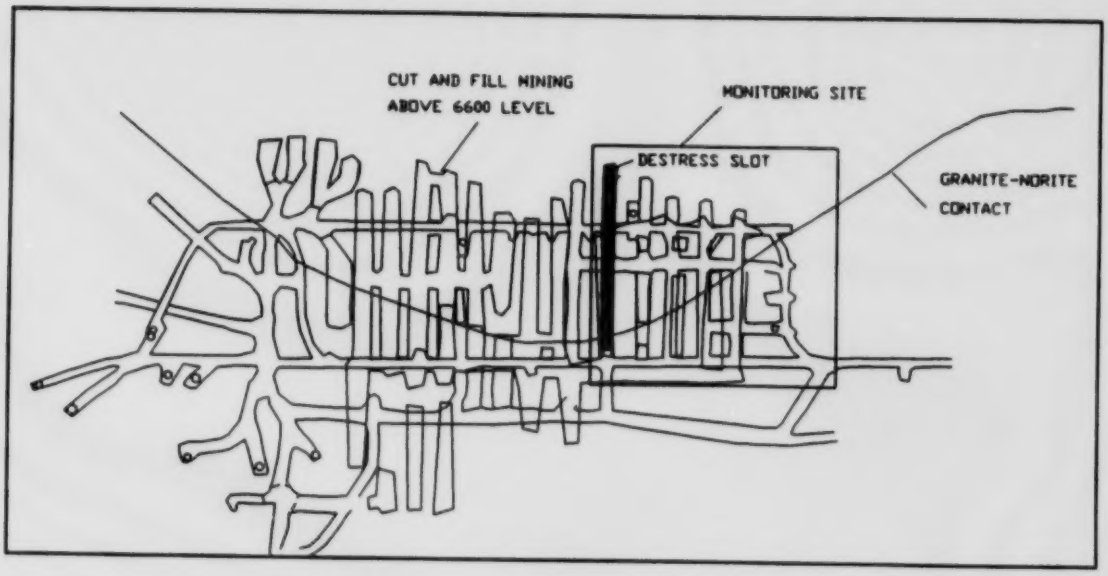

Figure 2-3 Creighton Mine, 6600 Level Plan

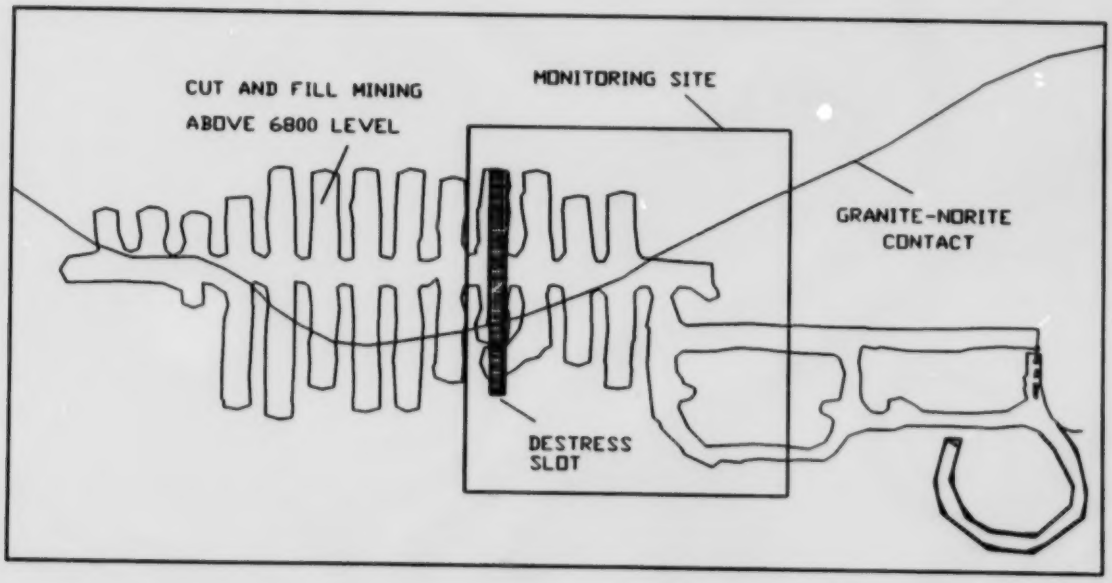

Figure 2-4 Creighton Mine, 6700 Level Plan

To the west of 4500 VRM block is 4300 MCF -- this was also converted to VRM mining during the monitoring program. Approximately 27 meters of ore separated the 4300 mining block from the level above while the destress slot was being excavated.

The changing geometry of the actual monitoring site and adjacent mining is detailed in the Volume 3: Field Monitoring Program, while the geometry of the completed MCF mining, from 6600 level to 6000 level, is summarized in the BEM3D input file in Appendix A. The co-ordinates of the mined-out areas, prior to the mining of the destress slot, are given in this input data file. The geometry above 6600 level does not change throughout the monitoring period.

2.2 Geology

Within the 6600-6700 ore block at Creighton Mine, there is a subtle variation in the geology. The ore zone is primarily composed of massive sulphides, however there is a variable transgression into disseminated sulphide ore toward the hangingwall rocks. Norites are the primary constitutive rocks within the hangingwall zone while the footwall is predominately composed of granites, however, this zone is also interspersed with inclusions of gabbroic rocks. Although there rarely are definitive divisions between the geological lithologies within a rock mass, the Creighton case study area has been simplified in order to create representative numerical models. Three distinct geological zones have been delineated:

1) massive sulphides -- ore zone

2) granites -- footwall

3) norites -- hangingwall

2.2.1 Rock Properties

The *intact* versus *rock mass* parameters for the Creighton Mine case study are listed in Table 2-1. These values were used in the initial input for each numerical modelling study. The rock properties for these three lithologies have been defined from two main sources: from previous numerical modelling studies both at Creighton Mine and other INCO mining properties, and from geomechanical laboratory testing.

For each rock type, the undisturbed and disturbed rock mass values have been calculated using both the Hoek-Brown Failure Criterion and the Mohr-Coulomb Failure Criterion. The Strength versus Confinement-Stress relationship for each of these undisturbed and disturbed rock mass values are plotted in Figure 2-5, Figure 2-6, and Figure 2-7; these plots are representative of the ore, the norites, and the granites respectively.

The rock mass for the case study area has been assumed to be undisturbed. Furthermore, the Mohr-Coulomb Failure Criterion values were used in all of the numerical modelling studies, as opposed to the Hoek-Brown values. The actual calculations for the Mohr-Coulomb Failure Criterion values and the Hoek-Brown Failure Criterion values are listed in Table 2-1.

These parameters have been further refined in the calibration modelling in order that the model results echo the instrumentation data and the historical ground behaviour.

ROCK TYPE	INTACT PROPERTIES	ROCK MASS PROPERTIES
Ore Zone: Massive Sulphides	E = 68.0 GPa ν = 0.25 C_o = 130 MPa m = 17.0 s = 1.0 density = 3000 kg/m^3 cohesion = 33.8 MPa ϕ = 35°	E = 23.7 GPa ν = 0.25 C_o = 57.4 MPa m = 4.87 s = 0.02047 RMR = 65 cohesion = 15.5 MPa ϕ = 33.26°
Norites	E = 79.0 GPa ν = 0.29 C_o = 155 MPa m = 17.0 s = 1.0 density = 2950 kg/m^3 cohesion = 36.2 MPa ϕ = 40°	E = 22.18 GPa ν = 0.29 C_o = 63.2 MPa m = 4.87 s = 0.0205 RMR = 65 cohesion = 16.5 MPa ϕ = 35°
Granites	E = 55.0 GPa ν = 0.25 C_o = 240 MPa m = 25.0 s = 1.0 density = 3000 kg/m^3 cohesion = 49.7 MPa ϕ = 45°	E = 25.1 GPa ν = 0.25 C_o = 97.8 MPa m = 7.42 s = 0.0229 RMR = 66 cohesion = 21.8 MPa ϕ = 42°

Table 2-1 Rock Properties

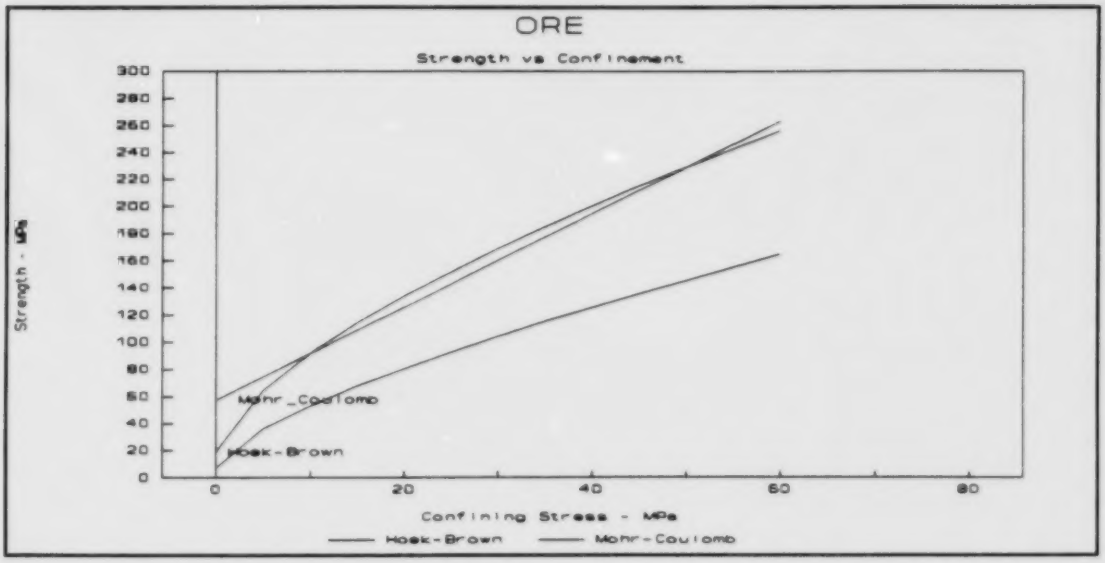

Figure 2-5 Ore: Strength vs Confinement-Stress

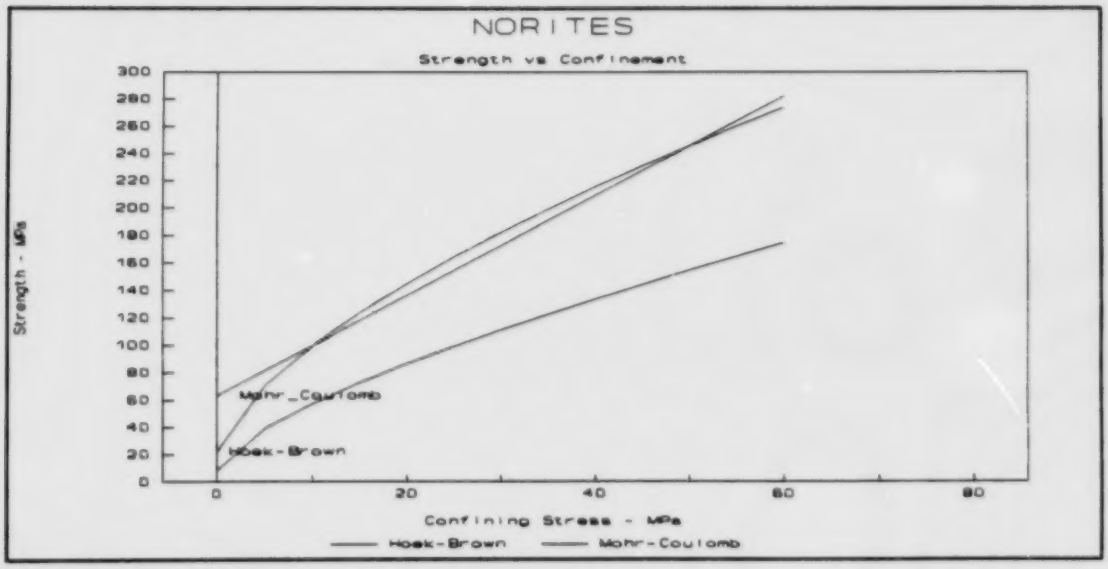

Figure 2-6 Norite: Strength vs Confinement-Stress

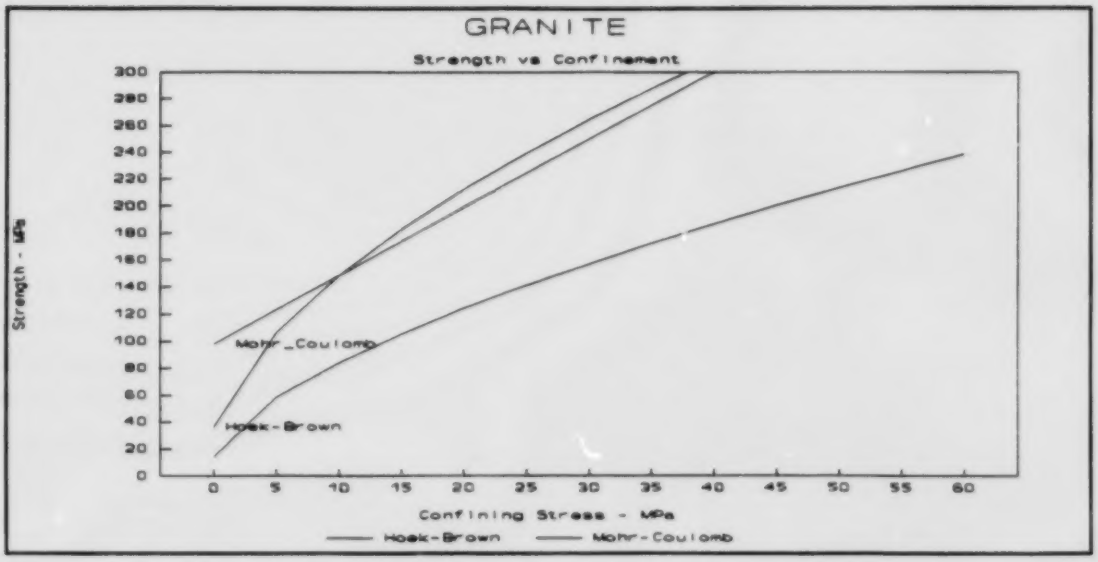

Figure 2-7 Granite: Strength vs Confinement-Stress

2.3 Field Stresses

A major overcoring program was undertaken by CANMET in Creighton Mine to define the field stresses in this area of the Sudbury Basin in 1974 and 1976 (Herget, G., 1975, 1977). The program consisted of the overcoring of both biaxial and triaxial stress cells at various depths in Creighton Mine. The tabulated results are shown in Table 2-2.

The magnitude of the major principal stresses vary from test to test at any given depth and with the type of stress cell overcored at that depth. Based on this data and from stress measurements obtained from various mines throughout Northern Ontario, the relationship for the major principal stress to depth obtained was:

$$\sigma_1 = 1.80 \times \text{Depth} + 10.83 \quad \text{(in MPa)}$$

The orientation of the major principal stress from the Creighton Mine measurements was fairly consistent at N65°E. This orientation is along the strike of the 400 ore body where the field monitoring program was conducted.

			MAJOR			INTER			MINOR		
LEVEL	EQUIP.	YEAR	MAG.	AZ.	DIP	MAG.	AZ.	DIP	MAG.	AZ.	DIP
4000	DOOR STOP	1974	80.5	243	6	39.9	358	76	36.5	150	22
5600	DOOR STOP	1974	129	249	10	100	350	52	61.9	152	37
6800	DOOR STOP	1974	133	91	18	125	194	34	123	337	49
7000	DOOR STOP	1974	78.4	274	12	66.0	17	26	39.2	149	54
4000	CSIR CELL	1974	60.5	250	13	45.5	348	35	34.4	144	52
4000	CSIR CELL	1976	34.4	93	12	19.9	348	47	13.1	194	40
5600	CSIR CELL	1976	131	68	0	112	339	61	68.8	158	28
5600	CSIR CELL	1976	83.9	248	7	53.7	133	73	40.6	340	15
7000	CSIR CELL	1976	61.2	265	8	37.1	142	74	26.8	358	13
7000	CSIR CELL	1976	64.0	266	22	39.2	159	35	28.9	22	46
7000	CSIR CELL	1976	82.5	267	2	48.1	175	28	42.0	20	61

Table 2-2 Creighton Mine: Measured Field Stresses

The similar magnitudes and interchanging orientations (Figure 2-8) of the intermediate and minor principal stresses indicates that they are orthogonal to the major principal stress and relatively hydrostatic. Based on the weight of the rock mass with depth and on the magnitudes measured during the overcoring, the relationship for the two stresses with depth are:

$$\sigma_2 = \sigma_3 = 1.29 \times \text{Depth} \qquad \text{(in MPa)}$$

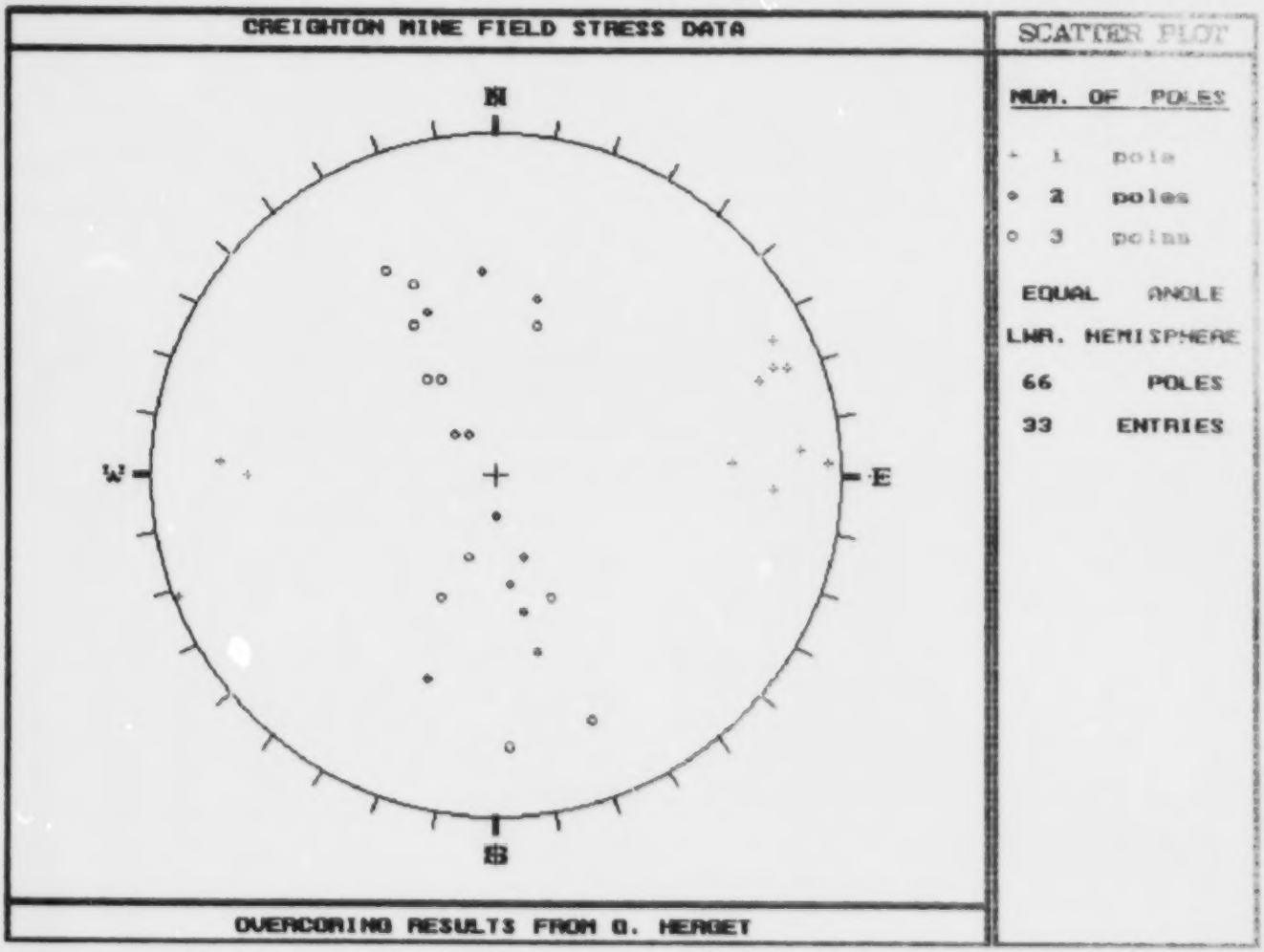

Figure 2-8 Magnitudes and Orientation of the Stresses at Creighton Mine

3.0 METHODOLOGY

A verity of different numerical codes were used in the calibration study with the intent of demonstrating the suitability of each to model the complex mining geometry of the monitoring site. Several similar codes (ie. Flac and MINE2D, 3DEC and MINE3D) were purposely used to allow those developed as part of this project to be compare the proven equi-dimensional plastic codes.

The different numerical codes were compared to the field data to differing degrees. Less emphasis was placed on the stresses and displacements calculated by the two dimensional models because of their questionable suitability for modelling the complex geometry of the monitoring site (non plane strain). The elastic BEM3D model does not calculate displacements and could be compared only to the stress magnitudes and stress relaxation zones measured during the monitoring.

The stress relaxation zones are areas where the rock mass had actually failed or where the mining geometry created stress shadows in areas that had not failed but were no longer in a state of high stress. It was not possible to distinguished between these different areas from the monitoring data. This has, consequently, lead to these areas being defined as zones of low stress or stress relaxation zones

The limitation of some of the codes resulted in them only being generally comparable to each other based on their estimated location of the stress relaxation zones which were measured at several different stages of mining during the monitoring program. The plastic codes all plotted failure and stress contours which were compared directly to the monitoring data. The BEM3D elastic model does not calculate failure and, therefore, could be compare only to the monitoring data by assuming that a factor of safety of one in the factor of safety contour plots was equivalent to the failure zones.

The methodology adopted in the calibration of all the numerical codes was to first define the input parameters (rock mass strength, friction angle, elastic modulus, cohesion, etc.) for the given code by modelling a known rock mass response from the monitoring site in the 400 ore body of lower Creighton Mine. These input parameters were then used in the modelling of the different stages of mining in the monitoring site and compared to the displacements (where applicable), stress magnitudes and failure zone locations obtained from the field measured data. The codes were then compared on the bases of their ability to match the field measured data and the degree to which the input parameters used in each code agreed with the field and lab. measured values.

This approach was taken because the numerical codes being used are not perfectly suited to simulate the rock mass response in such a

complex mining geometry as the monitoring site. In particular, the codes cannot represent non-homogeneous, multiple materials in a structurally controlled rock mass environment. Consequently, it was impractical to expect two dimensional elastic or plastic codes and three dimensional elastic continuum codes to simulate the rock mass response by simply inputting the measured material properties from the monitoring area.

4.0 3D ELASTIC MODELLING - BEM3D

The objective of this section of the report is to demonstrate the degree to which the three dimensional elastic boundary element program (BEM3D) can simulate the rock mass response to mining by modelling the general area around the monitoring site at Creighton Mine. Because it is a totally elastic code, the modelling results from BEM3D will not be directly comparable to all the field data collected from the monitoring site. The comparison is sufficient, however, to demonstrate the usefulness of 3-D elastic modelling in mining. A detailed explanation of the field monitoring program and the measured ground response to the progressive mining is given in Volume 3 "Field Monitoring Program".

4.1 BEM3D Numerical Modelling Program

BEM3D is based on the direct boundary element method. Uniform distributions of forces or displacement discontinuities are applied on each planer surface element. Details of this formulation are given by Wiles and Curran, 1982.

The three-dimensional elastic model employs planar, quadrilateral shaped surface elements which are positioned in three-dimensional space to form a continuous envelope around each excavation. In the boundary element analysis, forces are applied on these elements such that the surface normal and shear stresses are reduced to zero from their initial field stress values.

This accommodates opening interaction and results in the redirection of applied field loads around excavations, through pillars and abutments. A complete three-dimensional, geometrically accurate analysis can be conducted with this technique.

BEM3D requires the rock mass uniaxial compressive strength, Poisson's ratio, and angle of internal friction (Mohr-Coulomb failure criteria) as input data before any given model can be run. It also requires the principal field stress magnitudes with respect to depth and the principal stress direction with respect to the model co-ordinance be defined (see Appendix A for an example of the model input file) before a specific mining situation can be modeled.

The stresses, which are defined as σ_1, σ_2 and σ_3, are orthogonal to each other. σ_2 is always horizontal and σ_1 and σ_3 are defined with respect to σ_2 and the x-y axis. The orientation to this axis is defined in a counter-clockwise direction from the positive x-axis with the down dip being positive.

BEM3D will also allow the input rock mass properties to be defined using the Hoek-Brown failure criteria by giving the intact uniaxial

compressive strength of the rock mass and the appropriate m and s values for the rock strength.

The geometry that is being modelled requires the manual input of three dimensional co-ordinates to define the excavated areas. The shapes can be defined by surface plate elements or by block elements, whichever the user prefers. The geometric shapes can then be viewed on a 3-D pre-processor graphics program to ensure the proper definition of the model geometry.

BEM3D allows each block to be discretized individually to define the boundary elements that make up the model. A total of 2000 elements can be used in the present BEM3D program.

The location of the field point grids are also defined by manually inputting the appropriate co-ordinates. The field point grids can be defined either as 2-D or 3-D and can be viewed on the pre-processor with the model geometry.

BEM3D will also allow internal forces to be applied to individual elements to simulate a different stiffness in specific areas of the excavation. This approach was used in the following models to simulate the vertical stiffness of the backfill/rib-pillar combination in the cut-and-fill mining areas of the model.

The present version of BEM3D is run on MICRO-VAX 3900; a PC version of the code has been developed but is not totally functional at this time.

The output from the model is viewed on the same 3-D graphics program that is used as the pre-processor. The BEM3D output file gives the calculated principal stress at each field point as well as a factor of safety calculation. These can be viewed in the colour contour plots in the pre- and post-processor graphics program from which hard copy can be made. Displacements are not calculated by this code.

The output file allows the user to change the failure criteria input data in the post-processor (i.e rock mass angle of internal friction and uniaxial compressive strength for Mohr-Coulomb failure and s and m values and intact rock mass strength for Hoek-Brown) and have the newly calculated factor of safety graphically plotted in colour contour on the viewing screen. The post-processor will also allow the interchanging of the two failure criteria in the output file and again re-calculate the factor of safety for display on the screen.

4.2 BEM3D Modelling Sequence

Eight different stages of mining in the monitoring site were numerically modelled with BEM3D. These different mining stages

were all chosen because they were at a known rockmass state determined from the data collected during the monitoring program. The first two models run were used to calibrate the input parameters (ie. rockmass strength, friction angle and rib pillar/fill stiffness) for the elastic model. The remaining modelling was used to demonstrate the elastic codes suitability to simulate the rockmass response to the progressive mining by comparing the calculated results to the field measured data.

The first stage of the calibration process was to simulate the mining state prior to the conversion of the 400 orebody from MCF to VRM mining. The ore above 6600 level had already been excavated up to 6000 level using a MCF mining method (Figure 4-1). The result was that this area now contained a combination of hydraulically placed cemented tailings backfill and failed ore rib pillars (see Appendix A initial model input file).

The ore above 7000 level had been excavated to approximately 21 meters above that level using the MCF mining method. This left a 40 meter crown pillar between the existing mining elevation and 6800 level and 21 meters of fill/pillar material from 7000 to the existing mining elevation (6900 level). A similar situation existed above 6800 level but the mining had progressed to where

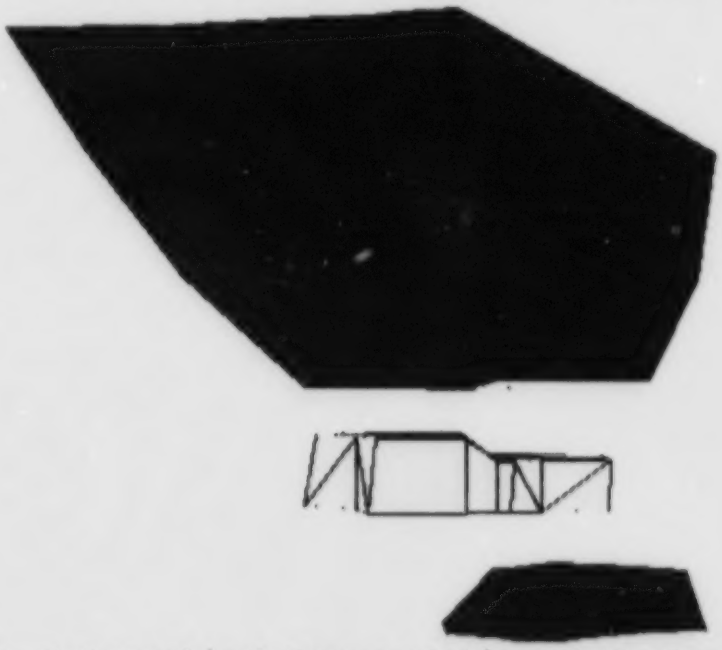

Figure 4-1 3-D Graphical Representation of the Numerical Model

only a 37 meter crown pillar remained between the mining and 6600 level and 24 meters of fill/pillar material from 6800 level to the existing 6700 level mining horizon.

These two crown pillars were known to be in an unfailed state at this stage of the 400 orebody mining. The mining geometry that existed at this mining stage was back analyzed as a first estimate of the proper input parameters for the model. The field monitoring program did not commence until after the initial conversion to VRM mining had started.

The next mining stage used to calibrate the input parameters for the elastic code was after a five panel destress slot had been mined through the crown pillar between 6600 and 6700 levels. The destress slot was mined as part of the conversion of this area from MCF to VRM mining.

This mining took place during the initial stages of the monitoring program when little instrumentation had yet been installed. The visual observations made in the monitoring area during these initial stages along with diamond drill core logging results did allow estimates of the stress relaxation zone to be made. These were compared to the modelling results as a further calibration of the input parameters.

The next three stages of mining that were simulated with BEM3D were the removal of the first three VRM panels in the 4500 mining block. Stress measurement data and stress relaxation zone locations defined for the mining of each of these panels were compared to the modelling results as a further calibration of the input parameters and a measure of the model's capabilities to properly simulate the rock mass response to the progressive mining in the site.

BEM3D, unfortunately, does not output any displacement or strain data. This meant that the displacements measured in the monitoring program could only be used to help determine which areas underwent stress relaxation rather than compare their magnitudes and directions to the numerical output. Such comparisons were made, however, in the plasticity modelling that is covered later in this report.

The final three stages in mining modelled with BEM3D are after the sixth, ninth and tenth panels had been excavated in the monitoring site. The areas of known stress relaxation were again compared to the simulated results along with several areas of known stress change obtained from stress monitoring in the site during the mining of specific panels.

4.3 Initial Input Parameters

A rock mass strength of 62 MPa and Poisson's ratio of 0.25 were

initially used for the elastic model. These values were based on past measurements made at Creighton Mine and on previous back analysis numerical modelling work done for lower Creighton ore body. An angle of internal friction of 35 degrees was chosen based on the laboratory results for the different intact rock mass material from this area that ranged from 35 to 45 degrees (see section 2.2). It was assumed that the rock mass friction angle should be on the lower end of the intact material range.

A vertical internal force of 6.9 MPa was initially used to simulate the expected increased stiffness of the pillar/fill combination over straight cemented fill. This force is based on the assumption that the backfill confined rib pillar does supply some vertical support in the mined out cut-and-fill area of the model. Because the rib pillars are all intersected by slots that allowed access from stope to stope, they are not assumed to carry any horizontal load between the hangingwall and footwall or any load along the strike of the ore body. It is the area shown in Figure 4-1 that contained the backfill/rib-pillar combination of material.

The field stress values used in the calibration were based on overcoring work done by CANMET in the 1970's (G. Herget 1977, 1975) at Creighton Mine as explained earlier in this report. The major principal stress was horizontal and was oriented along the strike of the ore body parallel to the x-axis. The other two principal stresses are orthogonal and hydrostatic and oriented in the vertical direction and parallel to the y-axis respectively.

Planer field point grids were used in all the BEM3D models run in this study. A mid height cross sectional grid through the monitoring site in 4500 VRM mining block was run with all the models along with several vertical grids directed along the strike of the orebody. The 25 by 25 field point grids calculated data across the monitoring site on a 5 meter by 5 meter interval on the horizontal and 5 meter by 3 meter interval on the vertical.

The planer grids were all concentrated in the monitoring site. An alternative three dimensional coarse grid was run in mining stages one and two to examine the state of the crown pillars between 6800 and 7000 levels and 6600 and 6800 levels. This 3-D grid had field points set on 12 meter intervals.

4.4 Modelling Results

The initial two BEM3D models were run on pre-monitoring mining stages. These models were used to calibrate the elastic code to the known ground response at these two stages of mining. The input parameters defined by this calibration were used in the subsequent models run to compare the calculated ground response to the field measured response at six different stages of mining during the monitoring period.

4.4.1 Input Parameter Calibration - Mining Stage One and Two

The first stage of mining in the monitoring site to be elastically modelled was the pre-conversion to VRM mining (Figure 4-2). The cut and fill crown pillars between 6600 and 6800 level and between 6800 and 7000 levels were known to be intact at this stage in the mining. This made for a suitable back analysis situation with which to define the rockmass strength for the elastic model and to determine the proper internal forces to apply to the mined out areas that contained a combination of cemented fill and remnant rib pillars. The areas containing straight cemented backfill are given no strength characteristics due to the low strength (0.2 MPa) of this consolidated material.

The initial elastic model was run with a rockmass strength of 62 MPa, an angle of internal friction of 35 degrees, a Poisson's ratio of 0.25 and a vertical internal force of 6.9 MPa to simulate the expected increased stiffness of the pillar/fill. These input parameters resulted in the model showing the crown pillars between 6600 and 6800 levels and 6800 and 7000 to be failed as indicated in the factor of safety plots in Figures 4-3 and 4-4. The extent of the pillar failure was progressively decreased by

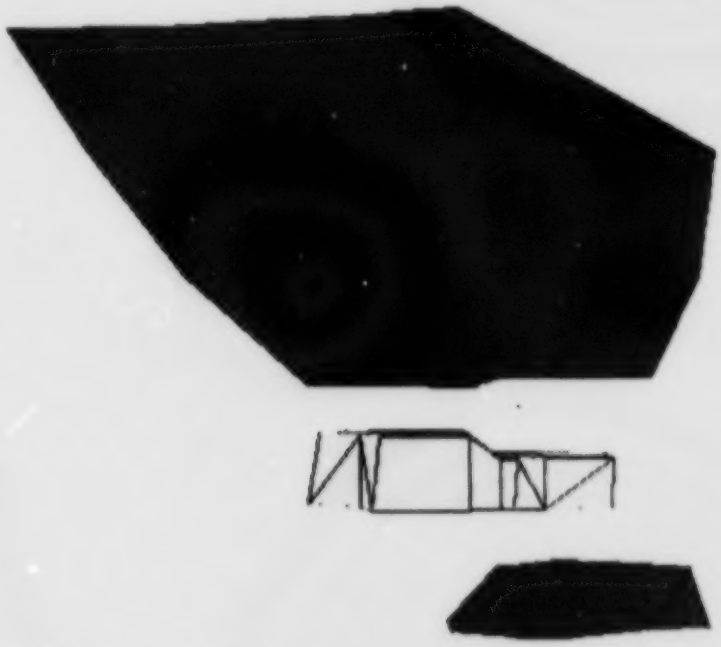

Figure 4-2 3-D Graphical Representation of Mining Stage One

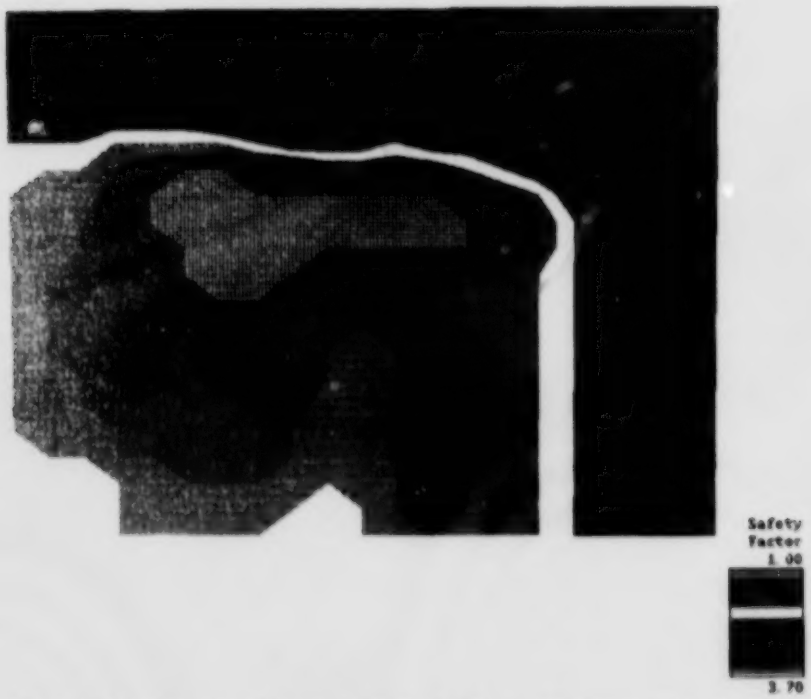

Figure 4-3 Mid-Height Section 4500 VRM - Factor of Safety Contour

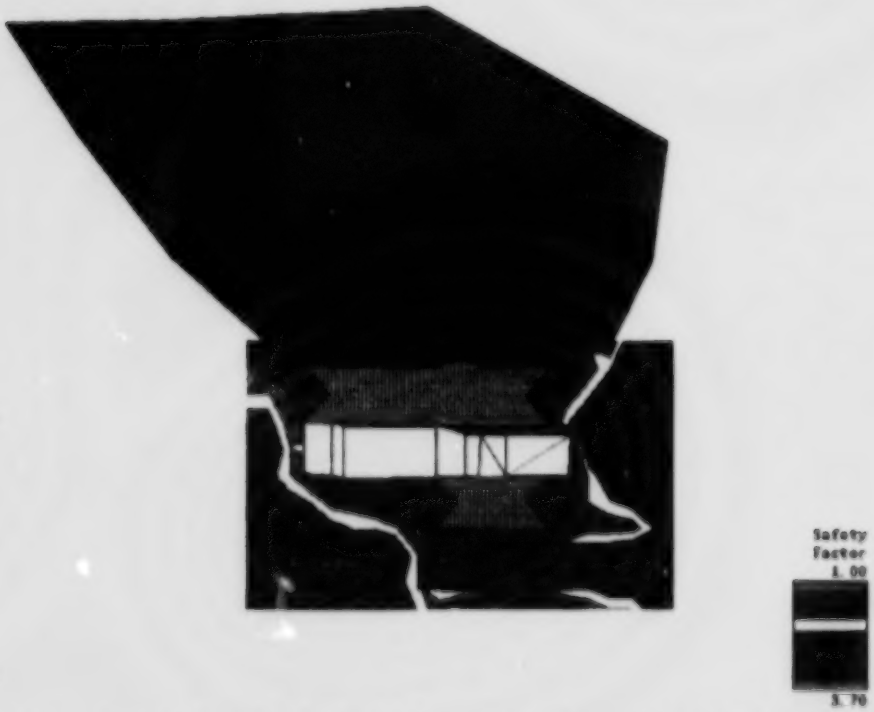

Figure 4-4 Longitudinal Section - Factor of Safety Contour Plot

rock mass strength. The crown pillar between 6800 and 7000 levels showed no failure at a rock mass strength of 69 MPa while the crown between 6600 and 6800 levels required a rock mass strength of 103 MPa or an angle of internal of 50 degrees before failure in the pillar was eliminated.

The results from the above modelling indicated that with a vertical internal force of 6.3 MPa to simulate the stiffness of the rib pillar/fill combination, and a 35 degree angle of internal friction, a rock mass strength of 103 MPa is required to allow the elastic model to reproduce the rock mass response to the mining in lower Creighton Mine. A similar rock mass response could be obtained with a rock mass strength of 62 MPa but a high friction angle of 50 degrees.

A rock mass strength of 103 MPa is much higher than what was indicated by previous back analysis and in situ testing and is thought to be unrealistic for this rock mass. It is also thought, based on the material property testing of the materials that made up the monitoring area that an angle of internal friction of 50 degrees is impossible in this rock mass.

This suggested that the internal force applied to the mining areas containing the rib pillar/fill combinations may have been lower than necessary to simulate this material strength. Consequently, a second model of this mining stage was run with a higher vertical internal force of 13.6 MPa to simulate an increased stiffness for the pillar/fill combination. Even with the high stiffness, the model still required a rock mass strength of 103 MPa to prevent failure in the crown pillar between 6600 and 6800 level.

It was concluded that this three dimensional elastic continuum code could not be used to simulate this stage of the mining in the 400 orebody. The structural mechanisms associated with the two crown pillars between 7000 and 6600 levels in lower Creighton Mine could not be reproduced by the BEM3D code to prevent failure from occurring. This stage of mining could not be used to calibrate the elastic code.

The next attempt to calibrate the code was at the post destress slot mining state. It was at this stage of mining in the 400 ore body that the monitoring program began. Little instrumentation was in place at that time in 4500 VRM mining block but the initial inspection of the monitoring area was well under way. The location of the stress relaxation zone in 4500 block, shown by the hatched lines in Figure 4-5 was estimated by a combination of visual observation and measurements in the mining area access drifts and from the logging of core obtained from diamond drilling conducted in the monitoring site at that time.

The accuracy of this estimate was later confirmed through further definition of the relaxation zone by observations made down the

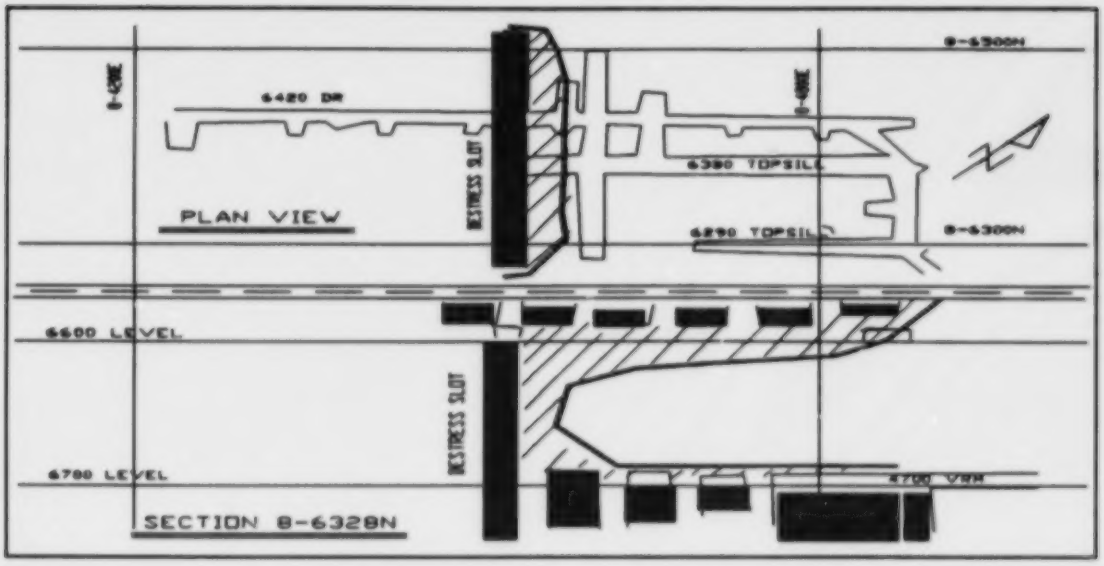

Figure 4-5 Plan and Section Showing Measured Stress Relaxation Zone

blast holes drilled to mine the VRM panels adjacent to the destress slot.

The initial BEM3D run of the stage two mining again used an initial rock mass strength of 62 MPa, a friction angle of 35 degrees and a internal vertical force of 6.9 MPa to simulate the material strength of the rib pillars and consolidated backfill areas. This combination of input data underestimated the extent of failure around the destress slot (Figures 4-6 and 4-7) as would be expected with any elastic model because the stress redistribution due to failure cannot be calculated.

Even with the angle of internal friction for the rock mass reduced from 35 to 30 degrees the model still underestimated the extent of the failure measured around the destress slot as shown in Figures 4-8 and 4-9. The general location of failure, however, agreed relatively well with the measured stress relaxation zone at this stage of the mining.

A second model at this mining stage was run with zero internal force to simulate the pillar/fill stiffness to determine if this would allow the model to better estimate the location of the failure zone. The model with the reduced pillar stiffness did little to change the extent of failure shown in the previous run and still underestimated the extent of failure.

Based on these results the input parameters for the remaining elastic modelling were kept at 62 MPa for the rock mass strength,

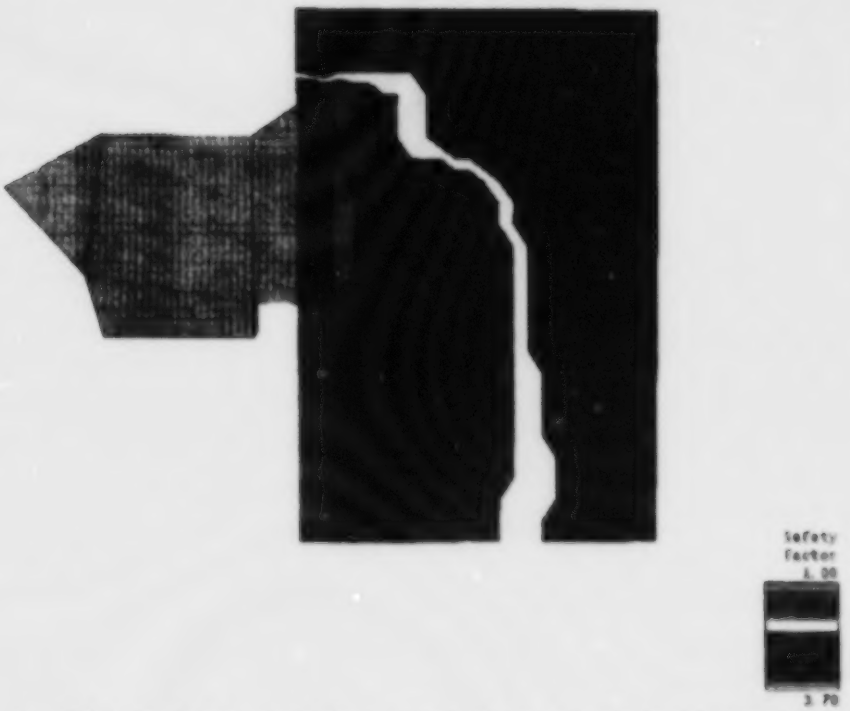

Figure 4-6 Mid-Height Section - Factor of Safety Contour Plot

Figure 4-7 Longitudinal Section - Factor of Safety Contour Plot

Figure 4-8 Mid-Height Section - Factor of Safety Contour Plot

Figure 4-9 Longitudinal Section - Factor of Safety Contour Plot

35 degree for the friction angle and 6.9 MPa material strength for the rib pillars and consolidated backfill areas.

4.4.2 Calibration to Field Data - Mining Stages Three to Eight

Mining stage three was after the first panel in the monitoring site had been mined. A small portion of the instrumentation was in place for the mining of this panel and one overcoring stress measurement was obtained from a hangingwall location. More importantly, the first television camera logging of the inspection boreholes that had been drilled into 4500 miming block was completed directly after the mining of this first panel. This produced an accurate estimate of the areas in the monitoring site that had undergone stress relaxation (as shown by the hatched lines in Figure 4-10) or stress increases.

The first modelling of the third stage of mining was run with the input parameters defined in the initial part of the elastic modelling study. The factor of safety contour plots (Figure 4-11 and 4-12) of the monitoring site for this model shows an under estimation of the relaxation zone with a rock mass strength of 62 MPa.

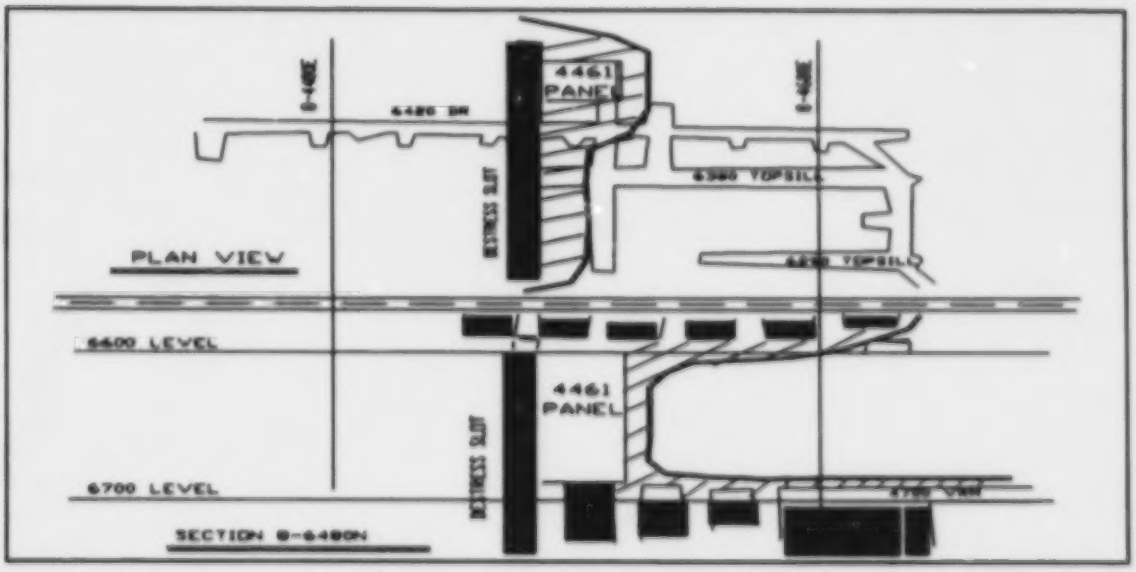

Figure 4-10 Plan & Section Showing Measured Stress Relaxation Zone

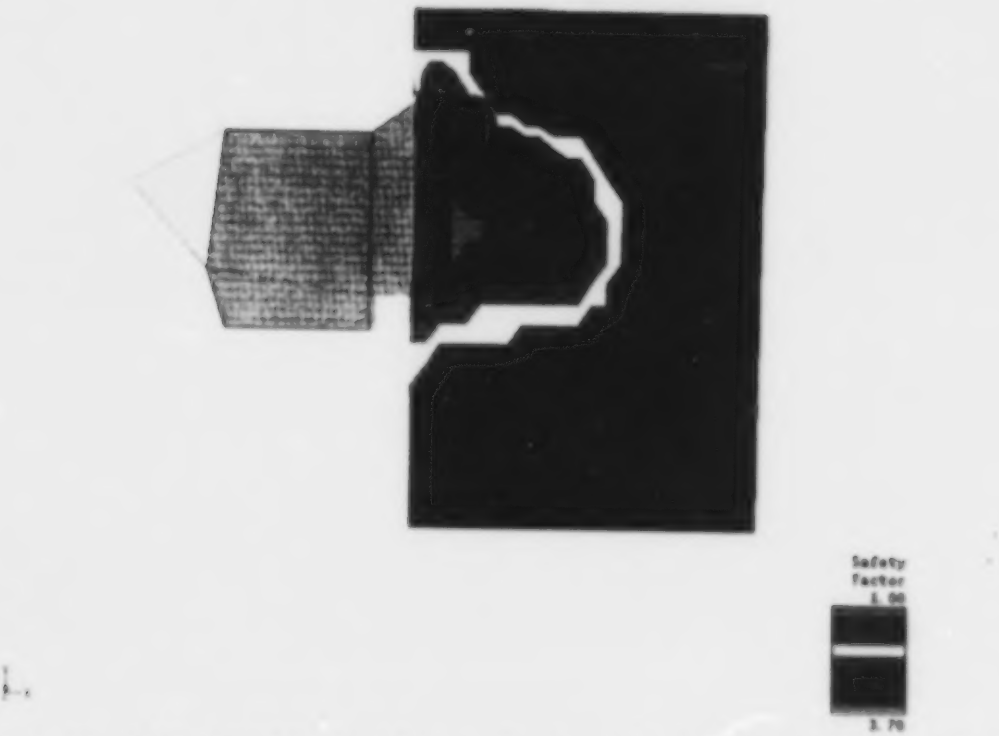

Figure 4-11 Mid-Height Section - Factor of Safety Contour Plot

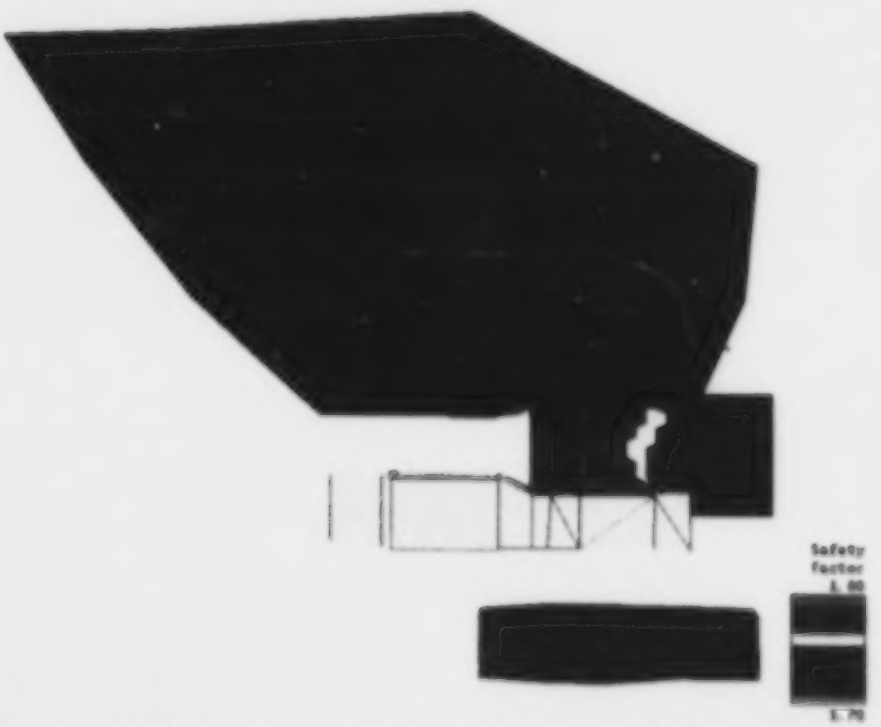

Figure 4-12 Longitudinal Panel 1 Section-Factor of Safety Contour

This resulted in the model for this mining stage being re-run with a zero stiffness for the pillar/fill mined out areas which, as in the previous model, made little difference to the extent of failure calculated by the elastic code.

The magnitudes from the principal stresses that were measured from the overcoring of a stress cell in the hangingwall on 6600 level were compared to the principal stresses calculated for this location in the numerical model. The location of the overcoring site and the magnitudes and directions of the principal stresses measured are shown in Figure 4-13. The magnitude of the calculated principal stress are shown in contour plots of the 6600 level elevation of the monitoring site in Figures 4-14 to 4-16.

The stress magnitudes shown on the contour plots are for the numerical model run with a simulated pillar/fill stiffness of 6.9 MPa (σ_1= 96 MPa (14,000 psi), σ_2= 83 MPa (14,000 psi) and σ_3= 31 MPa (4,500 psi)) which do not agree well with the measured stress magnitudes (σ_1= 130 MPa, σ_2= 78 MPa and σ_3= 63 MPa).

The poor agreement between the numerically calculated stress magnitudes from an elastic code and the field measured values is understandable. An elastic code does not calculate the stress redistribution that results from the rock mass failure and will, therefore, always be in error near a zone of failure.

4.4.2.1 Mining Stage Four Modelling

Stage four of the mining was directly after the mining of the second VRM panel in the 4500 block. The majority of the displacement monitoring instrumentation was in place for at least part of the mining of this panel and a successful overcoring of a stress cell was completed shortly after the panel was excavated.

The second logging of the inspection boreholes with a television camera was also completed shortly after the second panel was mined. This visual information along with the displacement data allowed the location of the stress relaxation zone at this stage of the mining to be estimated as shown by the hatched lines in Figure 4.17.

This fourth stage of the mining in the monitoring site was modelled with BEM3D using a same input parameters the previous run (rock mass strength of 62 MPa, a friction angle of 35 degrees and a internal force of 6.9 MPa to simulate the strength properties of the combined pillar/fill areas of mining). The three dimensional elastic code again underestimated the extent of the stress relaxation zone but did show failure in the same general locations as was measured in the monitoring program at this stage of mining (Figures 4-18 and 4-19).

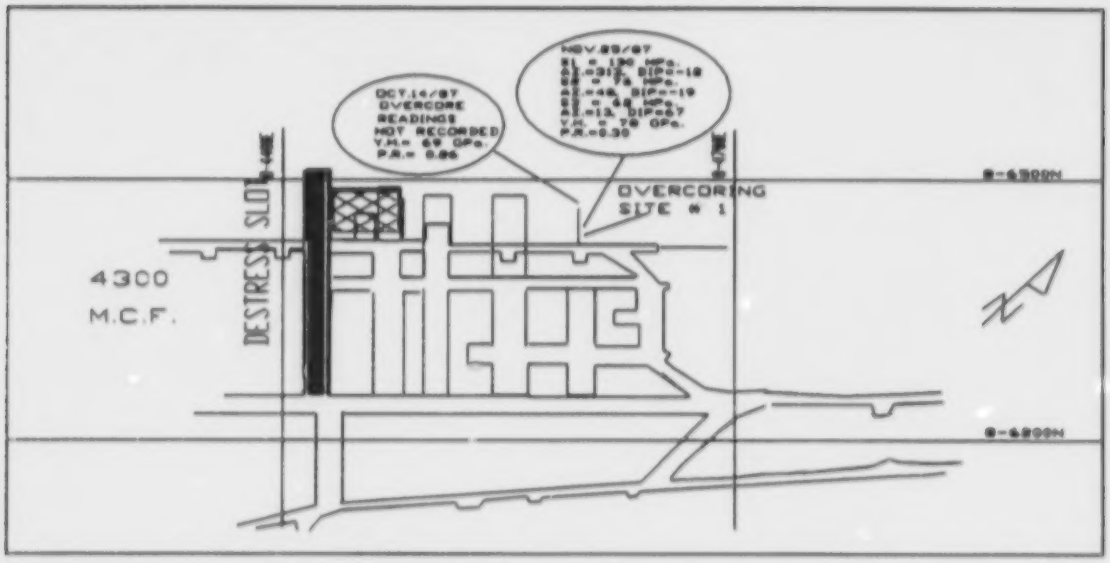

Figure 4-13 Plan 6600 Level Showing Overcoring Data

Figure 4-14 Plan 6600 Level - Major Stress Contour Plot

Figure 4-15 Plan 6600 Level - Intermediate Stress Contour Plot

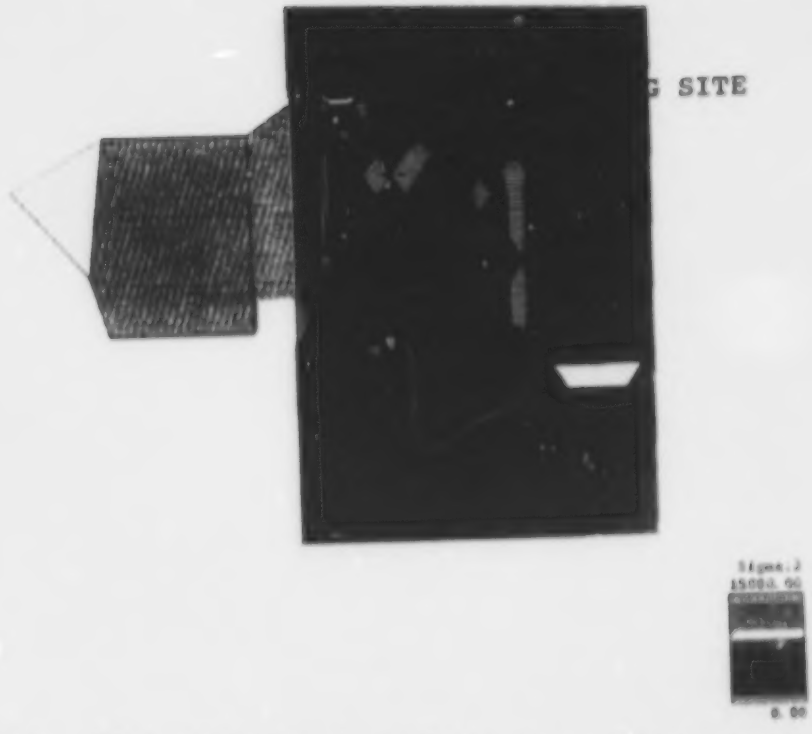

Figure 4-16 Plan 6600 Level - Minor Stress Contour Plot

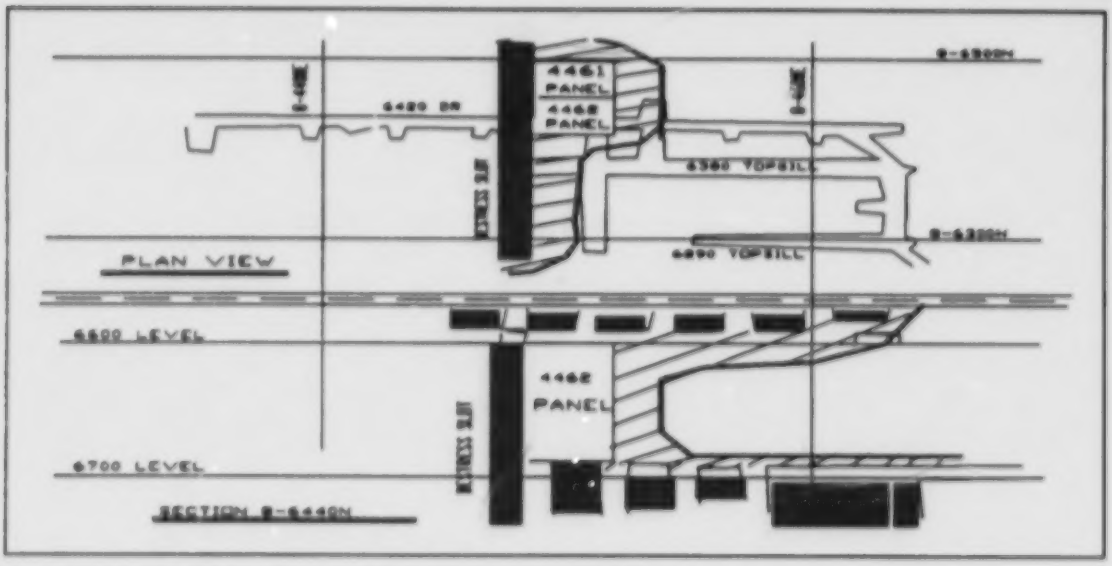

Figure 4-17 Plan & Section Showing Measured Stress Relaxation Zone

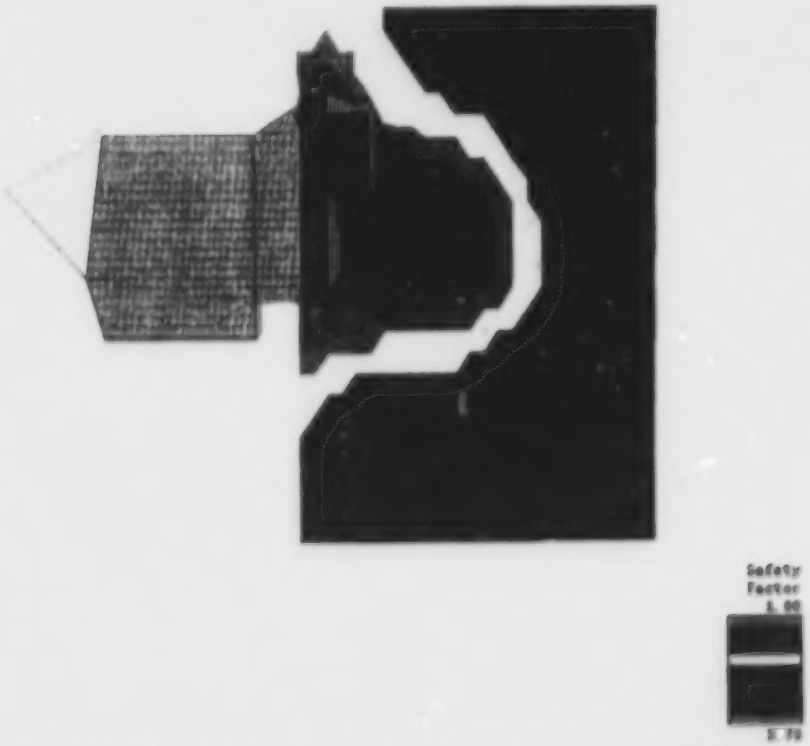

Figure 4-18 Mid-Height Section - Factor of Safety Contour Plot

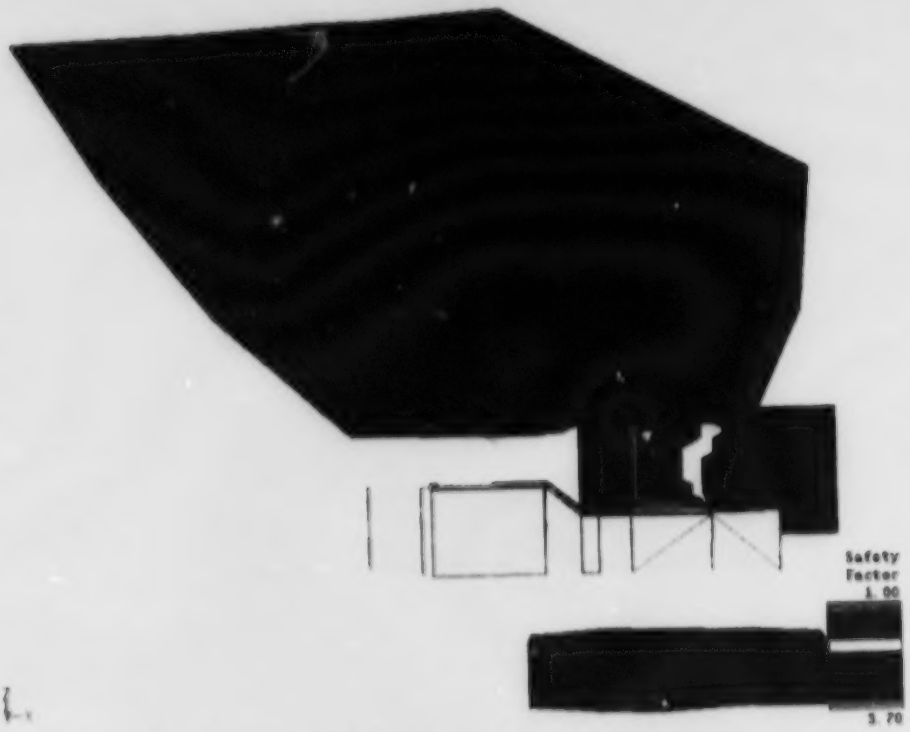

Figure 4-19 Longitudinal Panel 2 Sectionn-Factor of Safety Contour

The stress magnitudes calculated from the measured strains from the overcoring conducted on 6600 level after the mining of the second panel were again compared to the principal stresses calculated for this location in the numerical code. The location of the second overcoring site and the magnitudes and directions of the principal stresses measured are shown in Figure 4-20. The magnitude of the calculated principal stress from BEM3D are shown in contour plots of the specific area where the overcoring was conducted in Figures 4-21 to 4-23.

The stress magnitudes shown on the contour plots for the BEM3D model run (σ_1= 110 MPa (16,000 psi), σ_2= 62 MPa (9,000 psi) and σ_3= 31 MPa (4,500 psi)) again did not agree well with the measured stress magnitudes (σ_1= 43 MPa, σ_2= 16 MPa and σ_3= 7 MPa).

4.4.2.2 Mining Stage Five Modelling

The third panel mining in 4500 VRM block constitutes the fifth stage of mining in the monitoring site. It was at this stage of the mining that 4300 cut-and-fill mining block on the west side of the destress slot was converted to VRM mining. The first panel was removed from this site as panel three was being mined in the 4500 block.

The displacement instrumentation was all in place by this time and was monitored throughout this fifth mining stage. The displacement

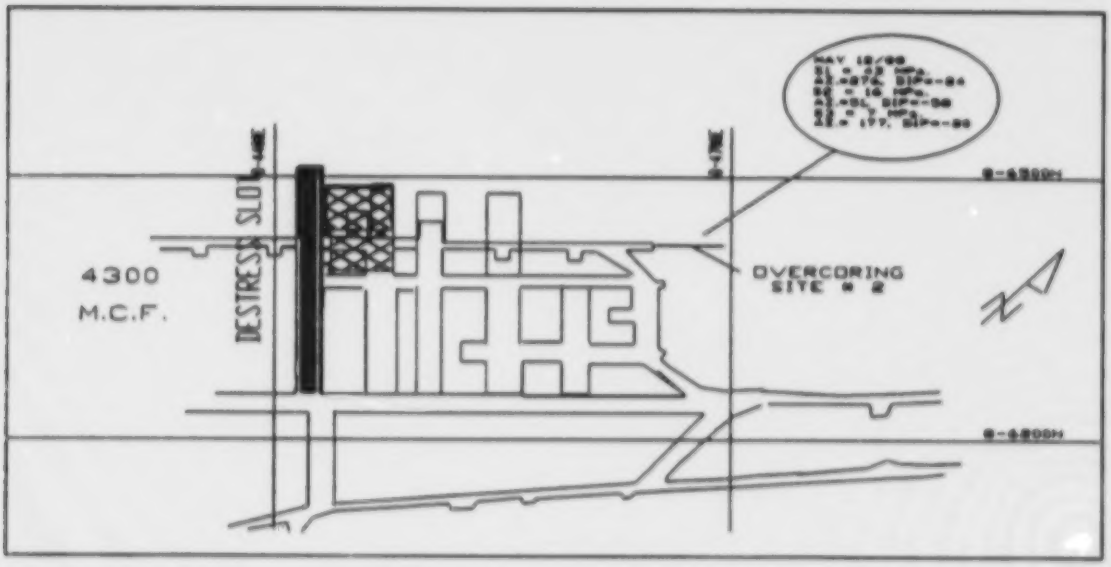

Figure 4-20 Plan 6600 Level Showing Overcoring Data

Figure 4-21 Plan 6600 Level - Major Stress Contour Plot

Figure 4-22 Plan 6600 Level - Intermediate Stress Contour Plot

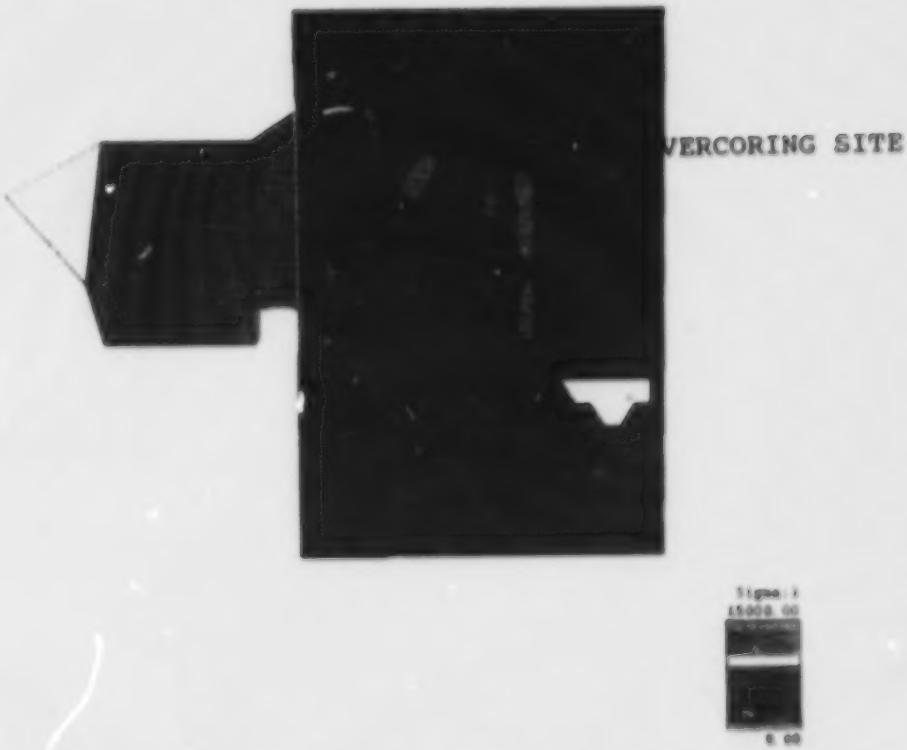

Figure 4-23 Plan 6600 Level - Minor Stress Contour Plot

data along with later visual observations made during the drilling of subsequent panels and borehole television logging allowed the location of the stress relaxation zone to be estimated as shown in Figure 4-24 by the hatched lines.

The third successful overcoring of a stress cell was completed after the mining of this panel at the same location on 6600 level as the previous stress measurement. The cell location and stress magnitudes and directions calculated from the strain measurements are shown in Figure 4-25.

The BEM3D modelling of this mining stage was run with the same input parameters as the previous stage. The factor of safety plots for this panel mining (Figures 4-26 and 4-27) show the stress relaxation zone again being made up of a combination of failed rock mass and stress relaxation adjacent to the newly excavated area. The model again underestimates the failure zone directly east of the panel which is known to be approximately 6 meters in width from visual observation made down the holes drilled in the subsequently mined panels. The length and depth of the relaxation zone agree well with its measured location.

The stress magnitudes from the overcoring (Figure 4-25) conducted after the mining of the third panel in the monitoring site agree fairly well with the principal stresses calculated for this location in the BEM3D model. The magnitude of the calculated principal stress from BEM3D are shown in contour plots in Figures 4-28 to 4-30 of the specific area where the overcoring was conducted.

The stress magnitudes for the BEM3D model run (σ_1= 110 MPa (16,000 psi), σ_2= 62 MPa (9,000 psi) and σ_3= 31 MPa (4,500 psi)) while not showing total agreement, compare fairly well overall with the measured stress magnitudes (σ_1= 117 MPa, σ_2= 69 MPa and σ_3= 48 MPa).

4.4.2.3 Mining Stage Six Modelling

The next stage of the mining that was modelled with BEM3D was after six panels had been excavated in 4500 VRM block. The displacement instrumentation had been in place for several panels and numerous other overcoring attempts had been made, unfortunately, without any further success.

The third logging of the inspection boreholes with a television camera was conducted at the end of this mining stage. The visual information obtained from the logging and from the drill holes of subsequently mined panels and from the displacement instrumentation lead to the estimation of the stress relaxation zone shown by the hatched lines in Figure 4-31.

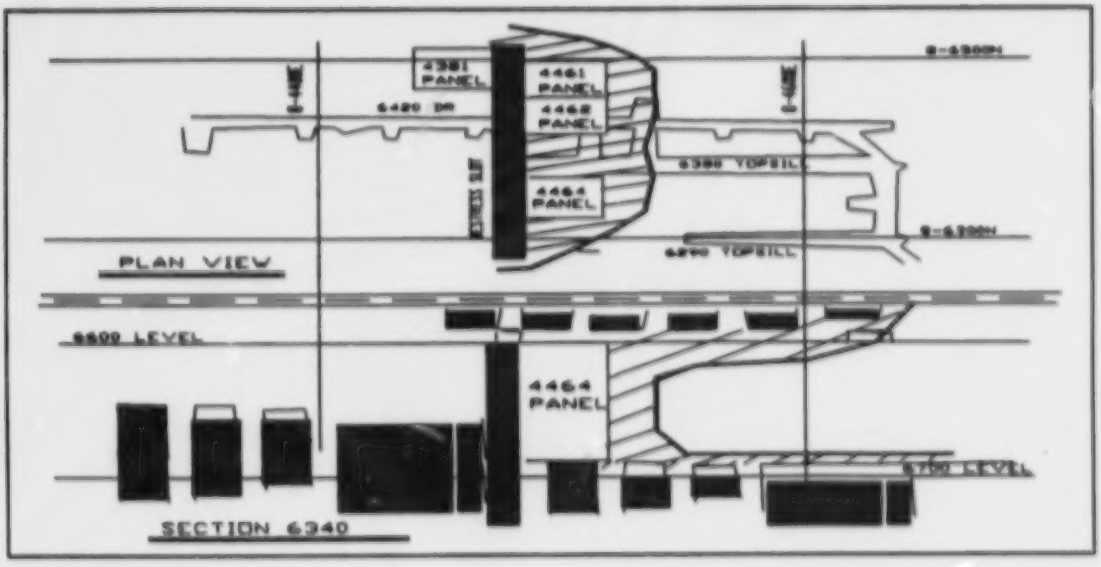

Figure 4-24 Plan & Section Showing Measured Stress Relaxation Zone

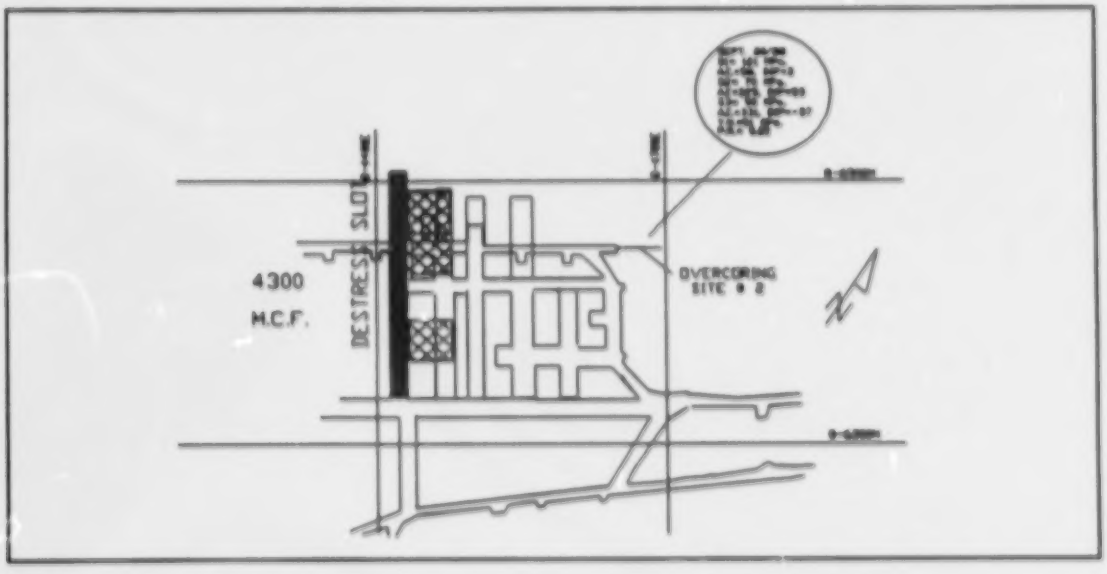

Figure 4-25 Plan 6600 Level Showing Overcoring Data

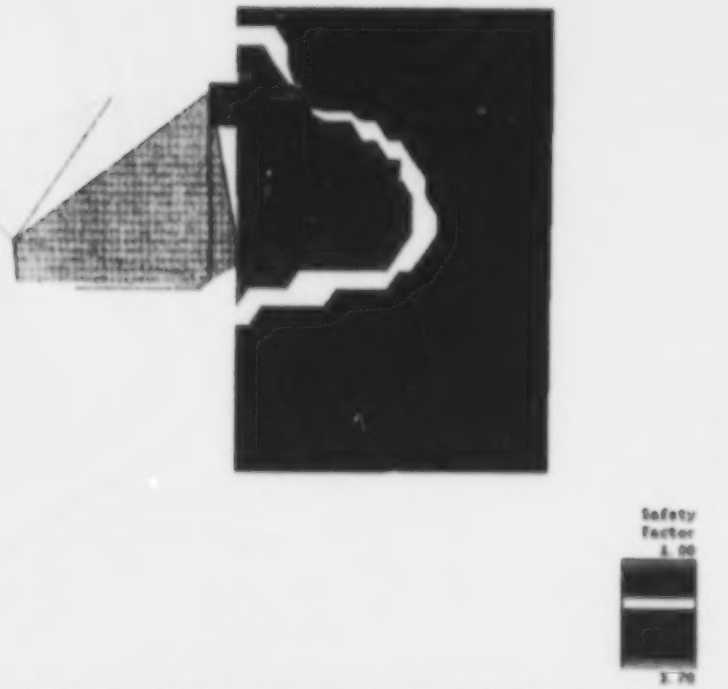

Figure 4-26 Mid-Height Section - Factor of Safety Contour Plot

Figure 4-27 Longitudinal Section Panel 3-Factor of Safety Contour

Figure 4-28 Plan 6600 Level - Major Stress Contour Plot

Figure 4-29 Plan 6600 Level - Intermediate Stress Contour Plot

Figure 4-30 Plan 6600 Level - Minor Stress Contour Plot

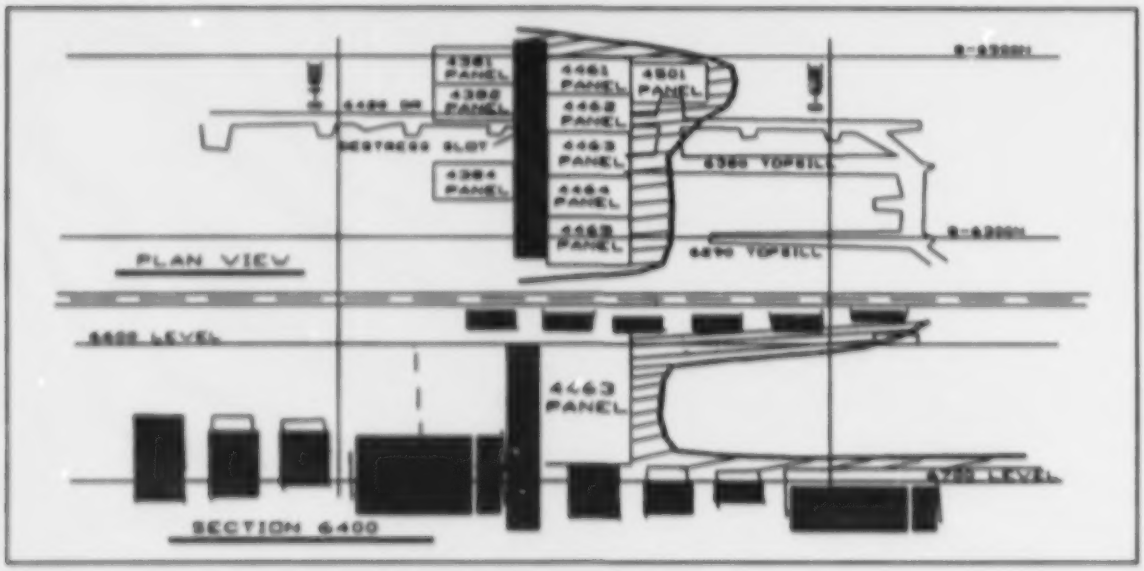

Figure 4-31 Plan & Section Showing Measured Stress Relaxation Zone

The BEM3D modelling of the 400 ore body, at this time in the monitoring program, also included the mining on the 4300 side of the destress slot where two further panels had been excavated. The model, with the same input parameters as used in the previous runs, again under calculated the size of the stress relaxation zone.

The factor of safety plots in Figures 4-32 and 4-33 show that the model underestimates the extent of the relaxation zone in front of the excavated areas. The zone was known to be approximately half the width of a single VRM panel at this location in the monitoring block. The model does agree with the general shape of the relaxation zone.

4.4.2.5 Mining Stage Seven Modelling

The mining of one of the three panels that took place between the sixth and seventh stage in 4500 VRM block caused the location of the relaxation zone to be moved substantially. Advancing the mining on the hangingwall out by one more panel caused a major stress redistribution in the monitoring site.

This was measured by a stress change monitoring cell that was

Figure 4-32 Mid-Height Section - Factor of Safety Contour Plot

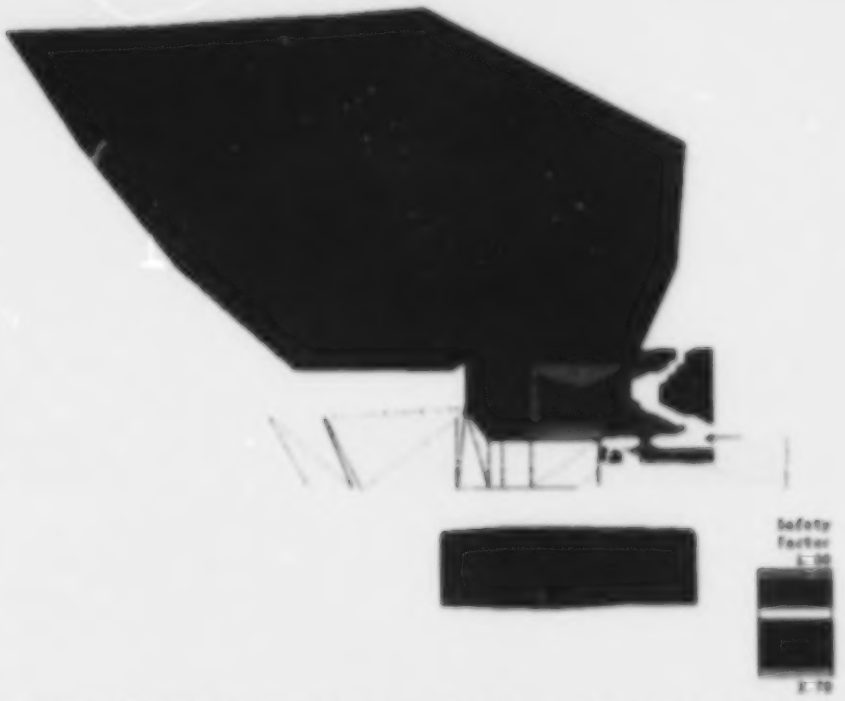

Figure 4-33 Longitudinal Section - Factor of Safety Contour Plot

installed in the hangingwall on 6600 level which showed a 0.41 MPa stress change at that point in the monitoring site when the crown was removed from this panel.

This was followed by the only Richter magnitude rock burst (2.0 in magnitude) measured in the monitoring site during the entire monitoring program which caused a 0.36 MPa stress change at the cell location. The burst was centred 15 meters below 6600 level and on a shear that runs along the ore/footwall contact. This type of a fault slip mechanism can not be simulated by the BEMJD continuum code.

The low magnitude of the stress changes does not make them very useful in the calibration of the BEMJD code. Stress changes of 7 MPa or greater would be necessary before a reasonable comparison to the stress changes in BEMJD can be made.

The location of the stress relaxation zone (Figure 4-34) was estimated from a combination of displacement data and visual observations made during the fourth logging of the inspection holes with a television camera conducted during this mining stage. This estimate was later confirmed by further observations made in the holes drilled in the subsequently mined panels.

The location of the relaxation zone from the BEMJD model run with the same input parameters for this mining stage shows it to be smaller than the measured area as shown in Figures 4-35 and 4-36.

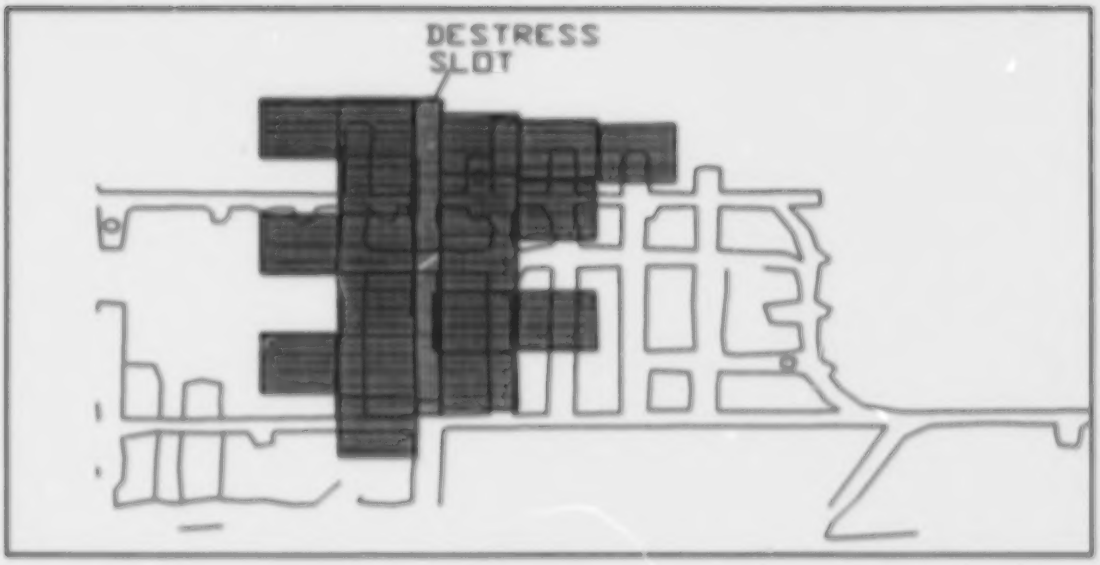

Figure 4-34 Plan & Section Showing Measured Stress Relaxation Zone

The general shape of the relaxation zone again agrees reasonably well with the measured field data.

It was at this stage in the monitoring program that block movement was measured in 4500 mining block adjacent to the footwall. This area consistently demonstrated movement along one or more structures located in the footwall area of the ore body. This type of failure cannot be simulated by the BEMJD model and may have contributed to the disagreement between the simulated versus measured rock mass response of the monitoring site at this and other stages of the mining.

4.4.3.6 Mining Stage Eight Modelling

The final stage of mining in the calibration of the BEMJD code to the field monitoring data was after eleven panels had been mined in 4500 VRM block. As with the previous mining stage, a substantial amount of VRM mining was conducted during this same time period on the 4300 side of the destress slot and in the crown pillar between 7000 and 6800 levels.

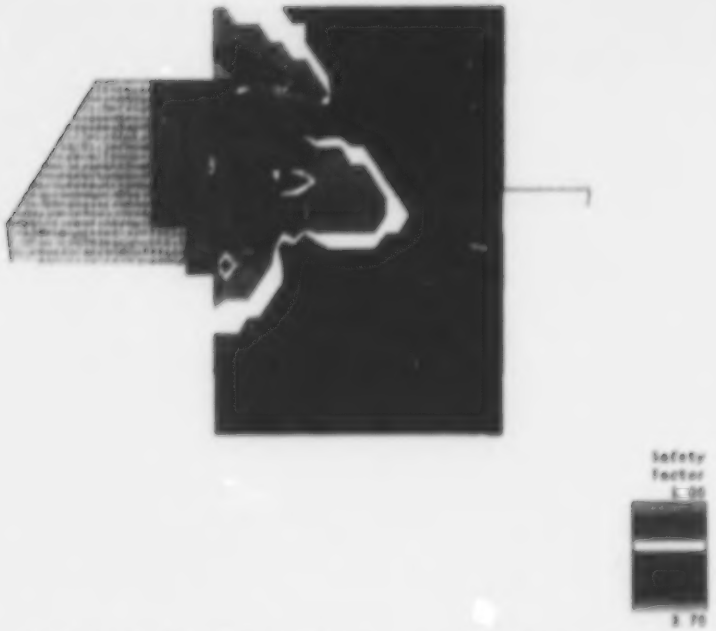

Figure 4-35 Mid-Height Section - Factor of Safety Contour Plot

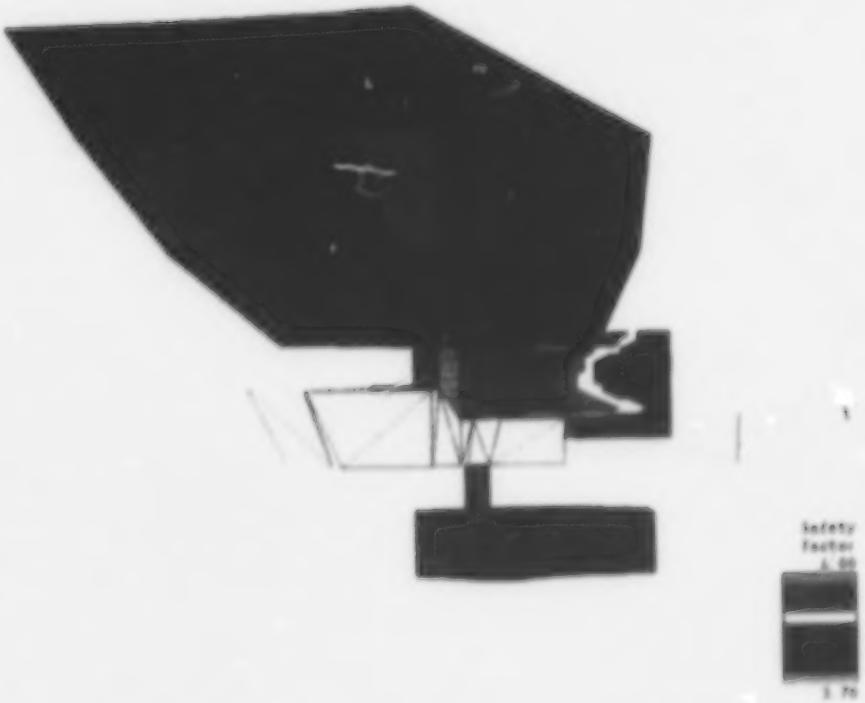

Figure 4-36 Longitudinal Section - Factor of Safety Contour Plot

The stress monitoring in 4500 mining block again showed stress redistribution during this mining stage but unlike the previous stage it was triggered by a footwall panel mining rather than a hangingwall panel. No stress changes were measured for the two panels mined on the hangingwall side of the monitoring site during this mining stage. The maximum stress change measured over this mining stage was 5.0 MPa which is too low to be used in the calibration of the BEM3D model.

The displacement data and the visual observation made from the borehole logging with the television camera showed the mining of the two hangingwall panels having little effect on the rock mass as demonstrated by the estimated location of the relaxation zone shown by the hatched lines in Figure 4-37. The footwall panel mining, however, caused a major shift in the zone location which was confirmed by the stress changes monitored and by an increase in seismic activity in the footwall during the panels excavation.

The BEM3D modelling results (Figures 4-38 and 4-39) show the mining of the hangingwall panels causing little change in the location of the relaxation zone which agrees well with the measured location of the zone at this mining stage even though it still underestimates the extent of the stres relaxation.

4.4 Summary of the Modelling With BEM3D

As demonstrated above, the BEM3D elastic boundary element numerical continuum code continually underestimated the extent of failure that will result from a given hardrock rock mass response to progressive bulk mining. Even with weaker rock mass properties the model could not simulate the behaviour measured in the rock mass by the monitoring program. The continued redistribution of stress in the 4500 mining block that resulted from the rock mass failure associated with the mining and the block movement accompanying this failure were beyond the limitations of this elastic code to simulate. The obvious consequence was a poor agreement between the model and the field measured data.

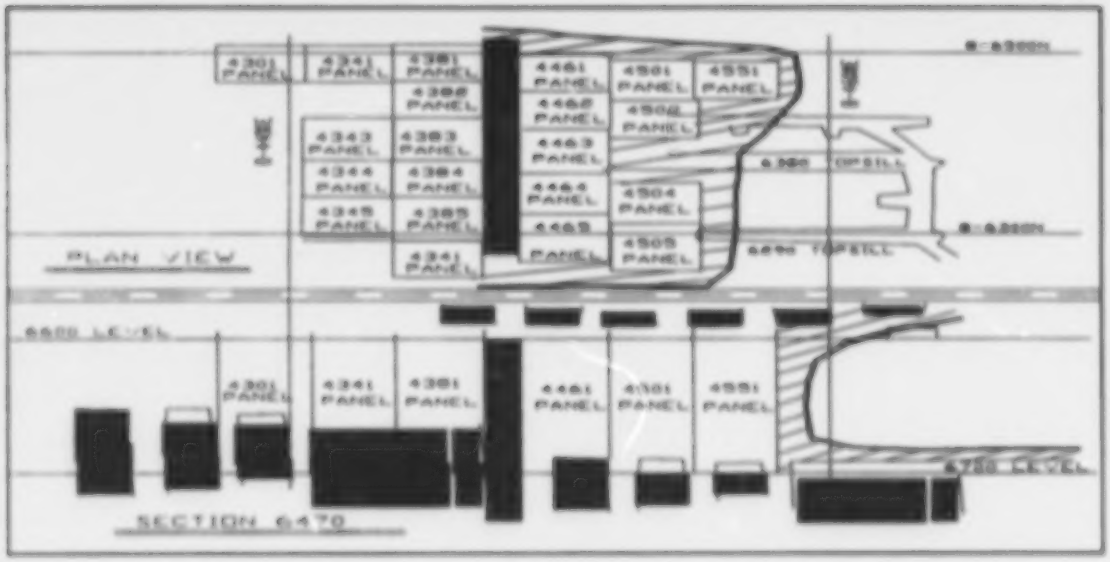

Figure 4-37 Plan & Section Showing Measured Stress Relaxation Zone

Figure 4-38 Mid-Height Section - Factor of Safety Contour Plot

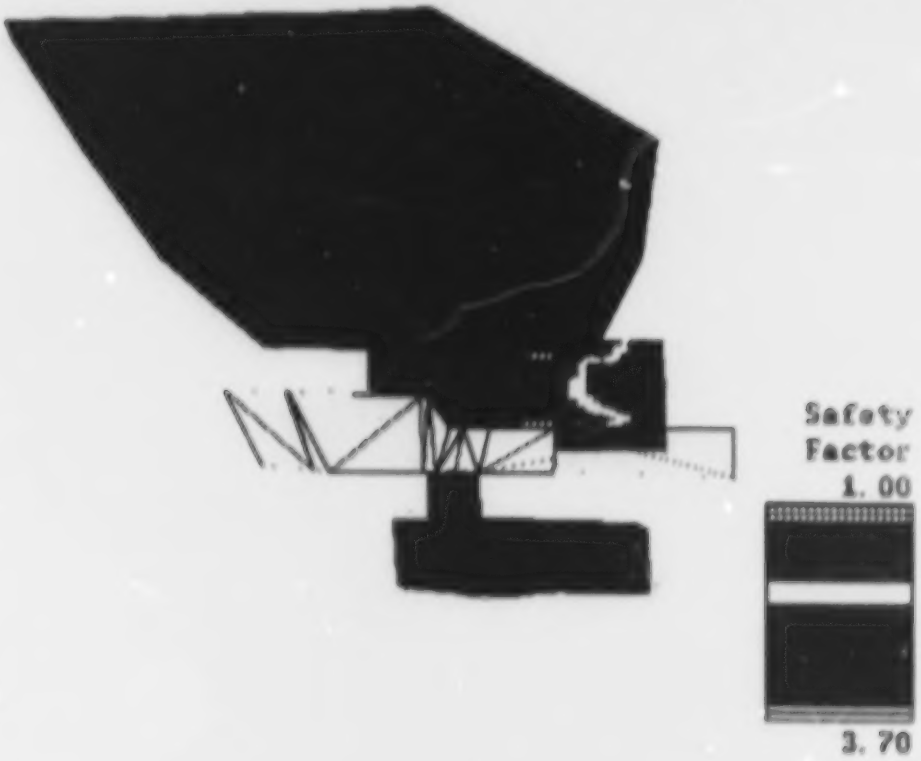

Figure 4-39 Longitudinal Section - Factor of Safety Contour Plot

5.0 2D PLASTICITY MODELLING

The ideal numerical modelling program, for either elastic or plastic modelling, is one which is able to provide answers to all of the modeller's concerns while employing a simple geometrical representation of the problem area.

There are a few commercially available plasticity programs, most of which can only model in two-dimensions. Although the condition of plane-strain cannot be truly met with any section through the Creighton case study site, a three-dimensional program which could simulate plasticity did not exist at Inco prior to the development of MINE3D. Inco did, however, have access to a 2D plasticity code called FLAC, (ITASCA Consulting Group, 1989).

The FLAC program has the ability to accommodate failure, which is one of the basic requirements for the calibration modelling of the Creighton Mine case study site. FLAC also has broad exposure world-wide and its validity has been extensively tested and proven. Despite its two-dimensionality, the FLAC code was considered to be appropriate for some of the calibration modelling of the 6600-6700 ore block.

Three 2D modelling geometries were used to simulate the mining in the 6600-6700 Ore Block; the models were calibrated with the field instrumentation data. The three geometries represent a plan section, a longitudinal section, and a vertical cross-section taken in various slices through the case study site. All three of the modelling geometries are less than ideal for two-dimensional modelling; they do no meet the required true, plane-strain conditions.

In the initial calibration procedure, the numerical modelling results were directly compared to the field data. An iterative process then ensued whereby the input parameters for the models were altered until the modelling results were qualitatively similar to the field data. In addition to achieving a correlation with the field data, the modelling results must also agree with the general knowledge of the ground behaviour throughout the mining history for the ore block.

There are two basic purposes for this calibration technique. The first and predominant purpose of the calibration modelling is to arrive at a set of input parameters which directly correspond to the 6600-6700 ore block. This derived set of data is to be used as initial input in the MINE3D numerical modelling program for the 3D, plastic, boundary element modelling of the 6600-6700 ore block.

The secondary reason for the 2D plasticity calibrations is to determine the legitimacy and effectiveness of using a two-dimensional plasticity model for determining the failure zone in the case study area.

5.1 FLAC (Fast Lagrangian Analysis of Continua)

FLAC is a two-dimensional numerical modelling program distributed by Itasca Consulting Group in Minnesota, USA. The program is based on an explicit finite difference formulation in which the medium within the model is considered to be a continuum. FLAC has the ability to model either purely elastic behaviour or elastic-plastic behaviour of a rock mass. With the plasticity modelling, FLAC is capable of predicting failure zones within the rock mass and/or backfill. The FLAC code is also capable of simulating the behaviour of a rock mass under either quasi-static or dynamic loading conditions. For the Creighton Mine modelling, it is assumed that the loading conditions are quasi-static. In further relation to the case study modelling, the other features offered and utilized with the FLAC program are the abilities for simulating multiple rock types, the effects of backfill, and specific in-situ stress levels. Some of the other plasticity modelling aspects for consideration are discussed within the following subsections.

5.1.1 Grid Specification

When preparing a FLAC model, the discretization of the grid is an important factor to determine. In some areas of the model, a high degree of accuracy is required; these areas are the zones of interest, where specific results are required. These areas should be enclosed within a finely-discretized grid while other, less critical areas of the model are usually set up with a coarser grid.

The specified grids for the three calibration models are a wrap-around variety. There are essentially two "small" grids which have been combined into one large one. The main grid is finely discretized in a central block, Figure 5-1(a); simulation of the mining is located within this grid. The other grid, which is gradually-coarser, is "wrapped" around the outer boundary of the fine grid in order to take the far-field effects into account, Figure 5-1(b). Even with this wrap-around technique, the "finer" grid zones in the calibration models are still quite large in dimension: 3 metres by 3 metres. As the overall number of grid zones (or elements) is increased, usually to accommodate a larger modelling area, the longer the problem will take to converge. For the three model geometries, the overall number of grid elements could not be increased to encompass a section through the entire mine unless the size of the "fine" grid elements was made larger (i.e. 10 metres by 10 metres). Such large-sized grid elements cannot be used in the central grid of the calibration models because a high degree of accuracy is required in this area which represents the crown pillar; the accuracy in the modelling results can only be obtained by using the smaller-sized grid elements. If these smaller-sized grid elements were used in a model of the entire mining geometry, the FLAC modelling problem would be huge and the corresponding run-time would be unacceptably large.

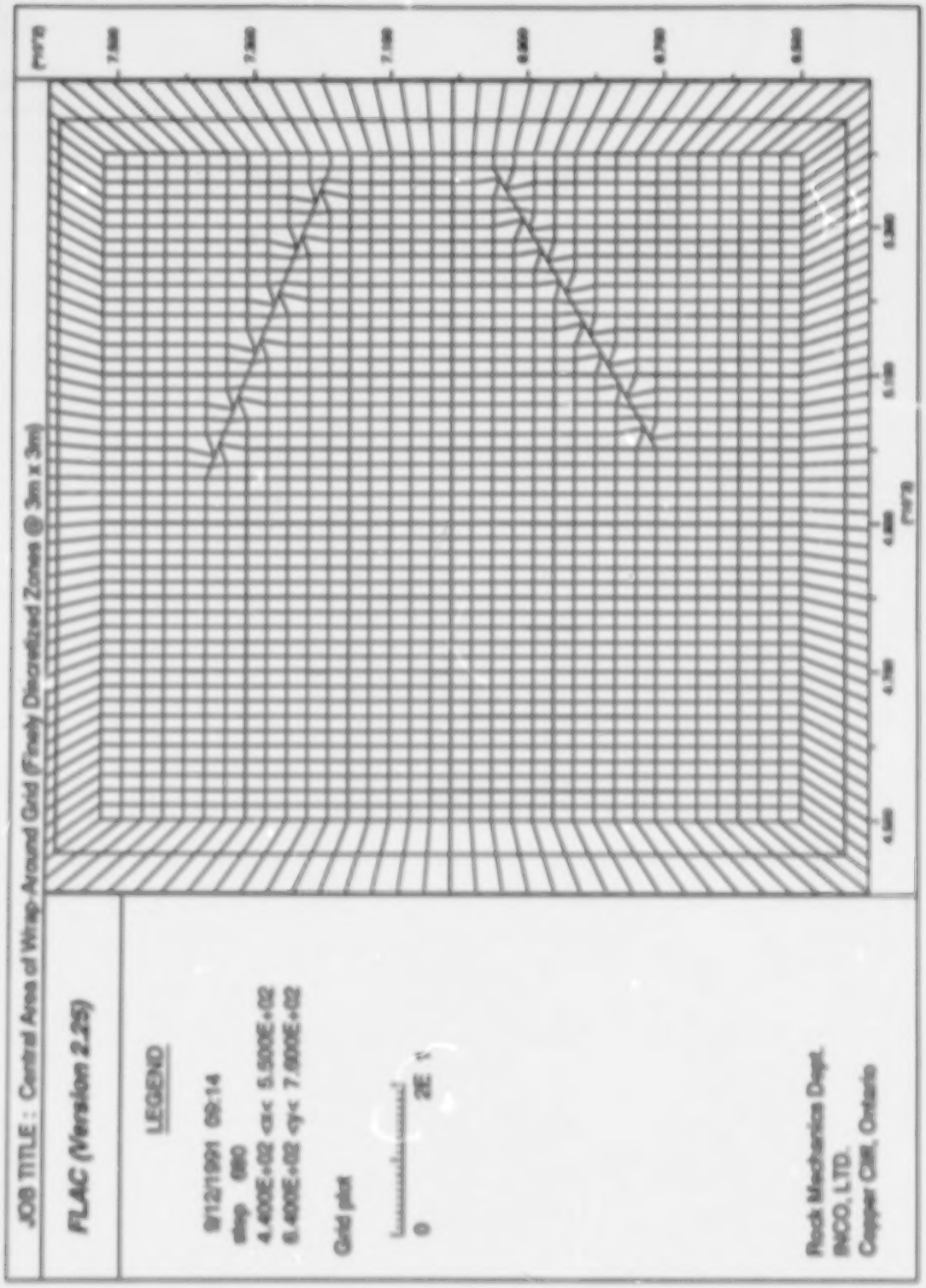

Figure 5-1(a) FLAC Wrap-Around Grid -- Central, Finely-Discretized Zones @ 3m x 3m

Figure 5-1(b) FLAC Wrap-Around Grid Showing Extent of Model. Mining is Located in Centre, see Fig. 5-1(a) for Magnification

5.1.2 Boundary Specifications

Once the central grid has been established, the extent of the outer boundaries must be determined. Also, the effect of the boundaries must be assessed for any possible influence on the results. Usually the boundaries are set at an appropriate distance out from the mining. A distance of 8- to 10-times the maximum span within the model usually provides a high degree of accuracy.

The actual distance to the boundary, however, depends on what is of interest to the modeller. The boundaries can be set closer if determination of failure is the only aspect under consideration. Likewise, the boundaries should be set out further when displacements are of importance. With the Creighton modelling, the boundaries were set at a distance equal to 8-times the largest span.

5.1.3 Plasticity Parameters

The required input parameters for a FLAC model depends on the type of geomechanics study that is to be performed. In order to determine a zone of failure in a rock mass, a Mohr-Coulomb plasticity model must be initialized. The required input parameters for the FLAC plasticity model are listed in Table 5-1.

Rock Properties:

Basic Elastic Properties:
- E - Young's Modulus
- ν - Poisson's Ratio
- B - Bulk Modulus
- S - Shear Modulus
- den - Density

Additional Properties for Plasticity Modelling:
- ϕ - Internal Angle of Friction
- coh - Cohesive Strength
- ten - Tensile Strength (optional)
- dil - Dilation Angle (optional)

Stress Values:
- sxx - stress in the x-direction
- syy - stress in the y-direction
- sxy - shear stress component

Table 5-1 Input Requirements for a FLAC Plasticity Model

5.1.4 Post-Processing

In terms of general output, the FLAC code can display a wide variety of results. With respect to the calibration models, the results of interest are the stress levels, the stress distributions, the displacements, and the extent of the failure zone.

The Figures within this report graphically represent the mining induced stress levels with contour plots, while the displacements are graphically displayed either as scaled vectors or as contour plots.

The zone of plastic failure, or the "state" of the rock mass, is graphically represented with various symbols for ease of interpretation. At any stage during the mining simulation, the "state" plot allows the modeller to observe either the predicted progressive failure or the sudden failure of the rock mass.

5.2 Calibration Methodology

The method of calibration involved iterative simulations for each of the modelling geometries. In the event that the model results did not correspond to the field instrumentation data and the historical rock mass behaviour, the input parameters were altered and the model was re-run.

The model was considered to be fully calibrated when the results echoed the actual ground behaviour at the case study site as well as the field monitoring data. Specifically, each model was calibrated on the basis of the stress magnitudes, the stress distributions, the displacements, and the predicted zone of plastic failure. The methodology of calibration for each of these specific parameters is described in further detail in the following sub-sections.

5.2.1 Calibration of the Stresses

Initially, the BEMJD models were calibrated with the field stress data. The predicted stresses in the 6600-6700 ore block were compared to the field data (overcoring and stress cells) until a close agreement between the model results and field data was achieved.

Once the BEMJD models were reasonably calibrated, the model results were used for defining the stress distributions and stress magnitudes at each stage in the mining history of the 6600-6700 ore block. The stress magnitude and stress distribution information was subsequently used in the calibration of the FLAC numerical modelling.

5.2.2 Calibration of the Displacements

When the predicted displacements from the FLAC models were compared to the measured displacements from the extensometers, the numbers did not match. There could be a number of reasons why the model data does not correlate with the field data. One reason could be due to the way in which the FLAC code simulates the modelling material; the rock mass is considered to be a continuum when in fact the displacements measured underground may be due to slip along discontinuities. In this case, the constitutive behaviour of the rock mass may not be the correct one for the case study site. Furthermore, the accuracy of the extensometer measurements is disputable. Because of an uncertainty in the accuracy of the field data *and* the model displacements, the calibrations of the model could not be made quantitatively. A qualitative calibration was made instead whereby the field data, regarding the incremental effects of mining, was used to calibrate the models. The field data was analyzed for the occurrence of large displacements; each of these occurrences can be associated with a particular mining step. Knowing *when* the large displacements occurred in the field, the numerical models were calibrated such that the results matched.

5.2.3 Calibration of the Failure Zone

The FLAC models were calibrated by comparing the predicted extent of the failure zone with the borehole instrumentation data and the VRM drilling data. For each model, the "state" plotting option is used to indicate where on the stress-strain curve that each portion of the rock mass has achieved. If the rock mass progresses into the plastic portion of the stress-strain curve, failure occurs.

In reality, the progression into the plastic state indicates some form of disturbance to the rock mass; the rock mass may appear fractured and broken up. In terms of field instrumentation, the borehole logging has established the division between plastic and elastic rock mass behaviour. The borehole logging has also delineated areas in the rock mass which have become destressed, or relaxed. This relaxation of the rock mass was not calibrated using FLAC, only the areas which experienced failure. The drilling of the VRM panels has also provided valuable field information as to the division of failed versus still highly-stressed ground. The calibrations were considered complete when the field data, delineating the failed ground, corresponded with the predicted failed area within the models.

Specific to the FLAC code, the "state" plotting option identifies grid elements which are "at yield". These elements may or may not be failed, depending on whether they have surpassed the yield point or not. For the purpose of estimating the zone of failure in the model, it is assumed that any portion of the rock mass which is "at yield" has indeed failed. Note, that within this report the term <u>failure</u> is not synonymous with the term <u>relaxation</u>.

The various states of the rock mass, using the FLAC plasticity model, are as listed (with reference to Figure 5-2).

Elastic Now and In Past- this describes the stress state where the field stresses do not reach nor achieve the rock strength. The rock mass follows the slope of the stress/strain curve. Elastic deformation occurs with no plastic failure.

At Yield- The field stress state has reached, but may not have exceeded, the yield point (rock strength) of the rock mass. No plastic deformation is experienced at the yield point. Yet, when the yield point is surpassed, the strain increases and plastic deformation occurs until equilibrium is reached. That is, the yield strength is achieved and movement occurs along the horizontal flat line portion of the stress-strain curve.

Yield in Past, Elastic Now- When the stresses exceed the rock mass strength, the strains increase and the rock mass undergoes plastic deformation until equilibrium is reached. With a redistribution of the stresses, the rock mass can behave elastically again, as long as the stress drops below the yield strength.

Tension Cutoff- The tensile strength of the rock mass is exceeded and tensile failure occurs.

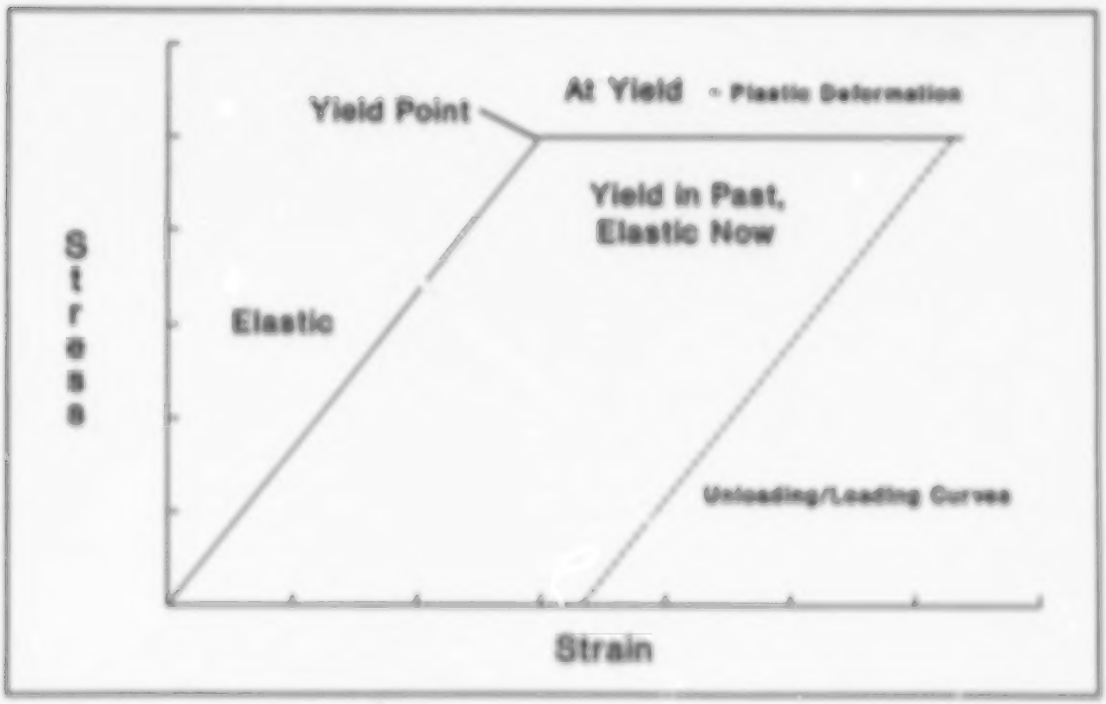

Figure 5-2 FLAC Stress-Strain Curve for Material Behaviour

5.3 Model Preparation

In order to set up the FLAC calibration models of the 6600-6700 ore block, there are some basic aspects to be delineated: 1) -the geology of the rock mass, 2) -the input parameters for each rock type, 3) -the material properties of the backfill, 4) -the field stress values, 5) -the modelling geometries, and, 6) -the mining sequences.

5.3.1 Geology

Within the 6600-6700 ore block, there is a subtle variation in the geology. The ore zone is primarily composed of massive sulphides, however there is a transgression into disseminated sulphide ore toward the hangingwall rocks. The hangingwall is largely composed of norites and the footwall is made up of granites with some inclusions of gabbroic rocks.

Although there rarely are definitive divisions between the geological lithologies within a rock mass, the Creighton case study area has been simplified for the set up of the numerical models. Three distinct geological zones have been delineated:

1) massive sulphides -- ore zone

2) granites -- footwall

3) norites -- hangingwall

5.3.2 Rock Properties

The *intact* versus *rock mass* input parameters for these three rock types are listed in Table 5-2. These values were used as the initial input parameters in the calibration modelling.

These initial parameters have been defined from two main sources: from previous numerical modelling studies both at Creighton Mine and other Inco mining properties, and from geomechanical laboratory testing.

For each rock type, the undisturbed and disturbed rock mass values have been calculated using the Hoek-Brown Failure Criterion and the Mohr-Coulomb Failure Criterion. The Strength versus Confinement-Stress Plots of the undisturbed and disturbed rock mass values are contained in Section 2 of this volume 4; these plots are representative of the ore, the norite, and the granite, respectively. The rock mass for the case study area has been assumed to be in the undisturbed category. As well, the Mohr-Coulomb Failure Criterion values were used to describe the rock mass behaviour in the FLAC calibration modelling, as opposed to the Hoek-Brown values.

ROCK TYPE	INTACT PROPERTIES	ROCK MASS PROPERTIES
Ore Zone: Massive Sulphides	E = 68.0 GPa ν = 0.25 C_o = 130 MPa m = 17.0 s = 1.0 density = 3000 kg/m^3 cohesion = 33.8 MPa ϕ = 35°	E = 23.7 GPa ν = 0.25 C_o = 57.4 MPa m = 4.87 s = 0.02047 RMR = 65 cohesion = 15.5 MPa ϕ = 33.26°
Norites	E = 79.0 GPa ν = 0.29 C_o = 155 MPa m = 17.0 s = 1.0 density = 2950 kg/m^3 cohesion = 36.2 MPa ϕ = 40°	E = 22.18 GPa ν = 0.29 C_o = 63.2 MPa m = 4.87 s = 0.0205 RMR = 65 cohesion = 16.5 MPa ϕ = 35°
Granites	E = 55.0 GPa ν = 0.25 C_o = 240 MPa m = 25.0 s = 1.0 density = 3000 kg/m^3 cohesion = 49.7 MPa ϕ = 45°	E = 25.1 GPa ν = 0.25 C_o = 97.8 MPa m = 7.42 s = 0.0229 RMR = 66 cohesion = 21.8 MPa ϕ = 42°

Table 5-2 Rock Properties

These parameters have been further refined in the calibration process in order that the model results echo the instrumentation data and the historical ground behaviour.

5.3.3 Backfill Properties

The FLAC numerical models require the inclusion of backfill in the excavations in order to more accurately represent the case study site. A 30:1 tailings-to-cement ratio, hydraulic backfill has been used in the filling of both the destress slot panels and the VRM panels. The mechanized cut-and-fill stopes, above and below the 6400-6700 ore block, require backfill properties which include the influence of rib pillars. This subject regarding the appropriate strength values for the backfill and rib pillar combination is addressed within a subsection of the FLAC modelling results.

The hydraulic backfill input parameters have been derived from some backfill testing and from some previous numerical modelling, ("The Convergence Resistance of Mine Backfills", D. Landriault and P. Oliver, 1989).

The input parameters for the cemented hydraulic fill assumes a 30:1 tailings to cement ratio and low confinement; the values are listed in Table 5-3.

Cemented Hydraulic Backfill-
Input Parameters for the FLAC Modelling

Elastic Properties:
E = 23.6 MPa
ν = 0.20
Bulk Modulus = 13 MPa
Shear Modulus = 11 MPa
density = 1800 kg/m^3

Plastic Properties:
cohesive strength = 0.067 MPa
ϕ = 33°
C_o = 0.25 MPa

Table 5-3 Hydraulic Backfill Properties for FLAC Modelling

5.3.4 Field Stresses

The FLAC program allows for two primary stress components and one shear stress component within a model. Also, the stresses can be initialized with a gradient. For example, the model could be set-up with an increasing vertical stress gradient in order to simulate the effect of depth in a vertical section. FLAC also allows for the effect of a gravitational force within a vertical section. The longitudinal and vertical cross-section calibration models both include gravity.

For the Creighton case study, the far-field stresses have been measured with the major principal stress being close to horizontal and along strike of the ore body, (Herget, 1986). Since the original overcoring, some additional information has been gathered on the near-field stresses at the instrumentation site, as described in Volume 3. It has been determined that the vertical and minor horizontal stresses are indeed hydrostatic and the major principal stress is horizontal. For the calibration modelling, the in-situ stress regime at the 6650 level is outlined in Table 5-4. The stresses used in the model are the far-field values.

	Magnitude MPa (psi)	Azimuth (in degrees)	Dip - down (in degrees)
σ_1	93.5 (13560)	100	0
σ_2	60.0 (8700)	190	-55
σ_3	60.0 (8700)	10	-35

Table 5-4 In-situ Stresses for the 6650 Level

5.3.5 Model Geometry

Three numerical modelling geometries were used for the FLAC calibration process. These simplified two-dimensional sections, taken through the instrumented area, were chosen in order to achieve a complete picture of the case study site in various directions. These sections are as follows:

1) - a level plan, taken approximately mid-height of the 6600-6700 ore block, at approximately the 6650 level, Figure 5-3.

2) - a simplified longitudinal section paralleling the long-axis of the ore zone, Figure 5-4.

3) - a vertical cross-section taken mid-strike along the ore body, Figure 5-5.

Each of these geometries is far from representative of the plane-strain conditions required for 2D modelling. However, the validity for using 2D modelling to simulate a 3D problem is not known until the models are each run and the results of each are compared.

Once each model is calibrated, whereby the results match both the field data and the general ground behaviour history of the 6600-6700 area, it is analyzed for validity. As well, the final three sets of input parameters are compared in order to determine the amount of discrepancy between them. Ideally, the input values should be the same for all three models since they each represent essentially the same area and the same history of mining.

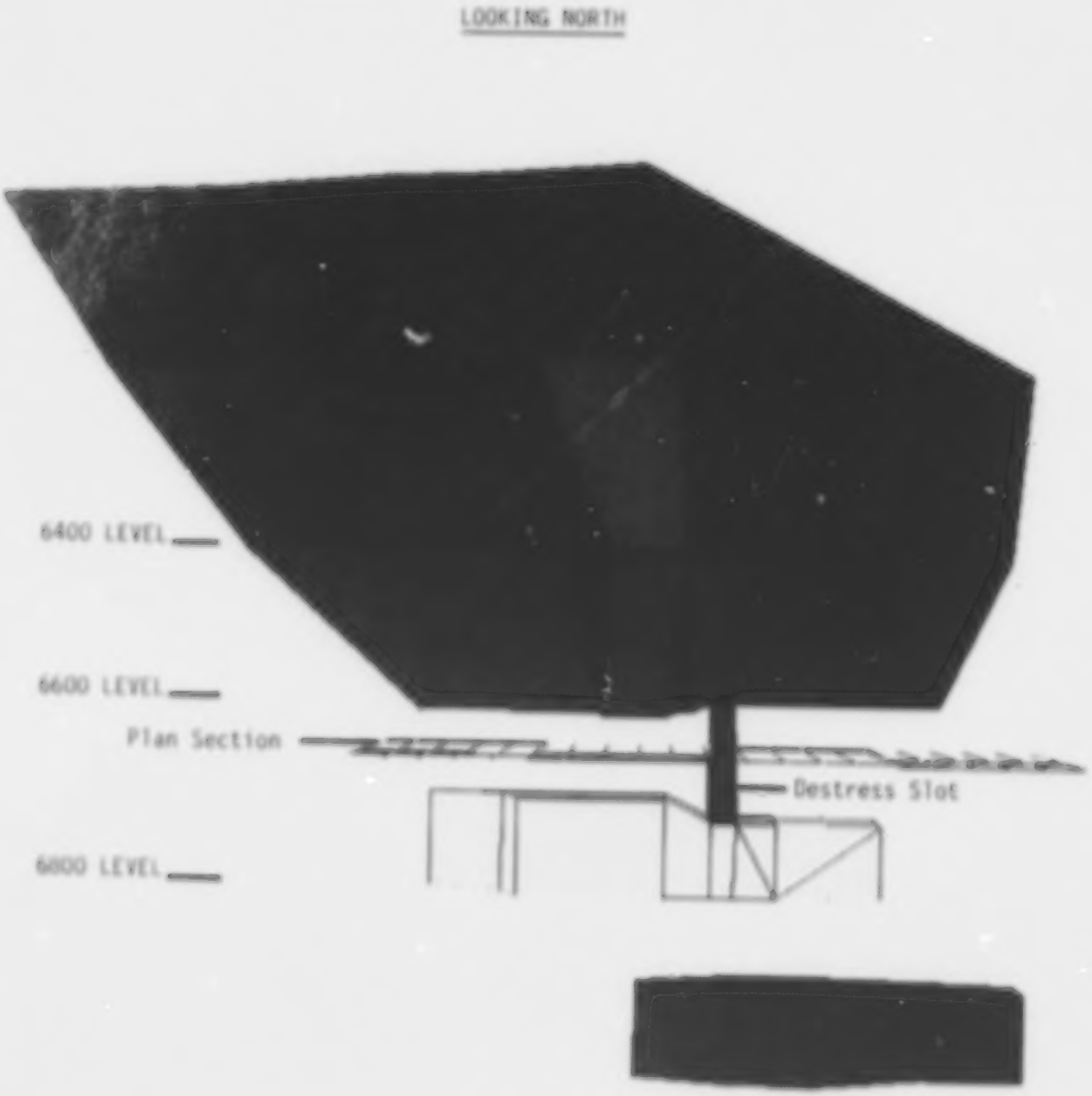

Figure 5-3 Location of Level Plan for FLAC Modelling

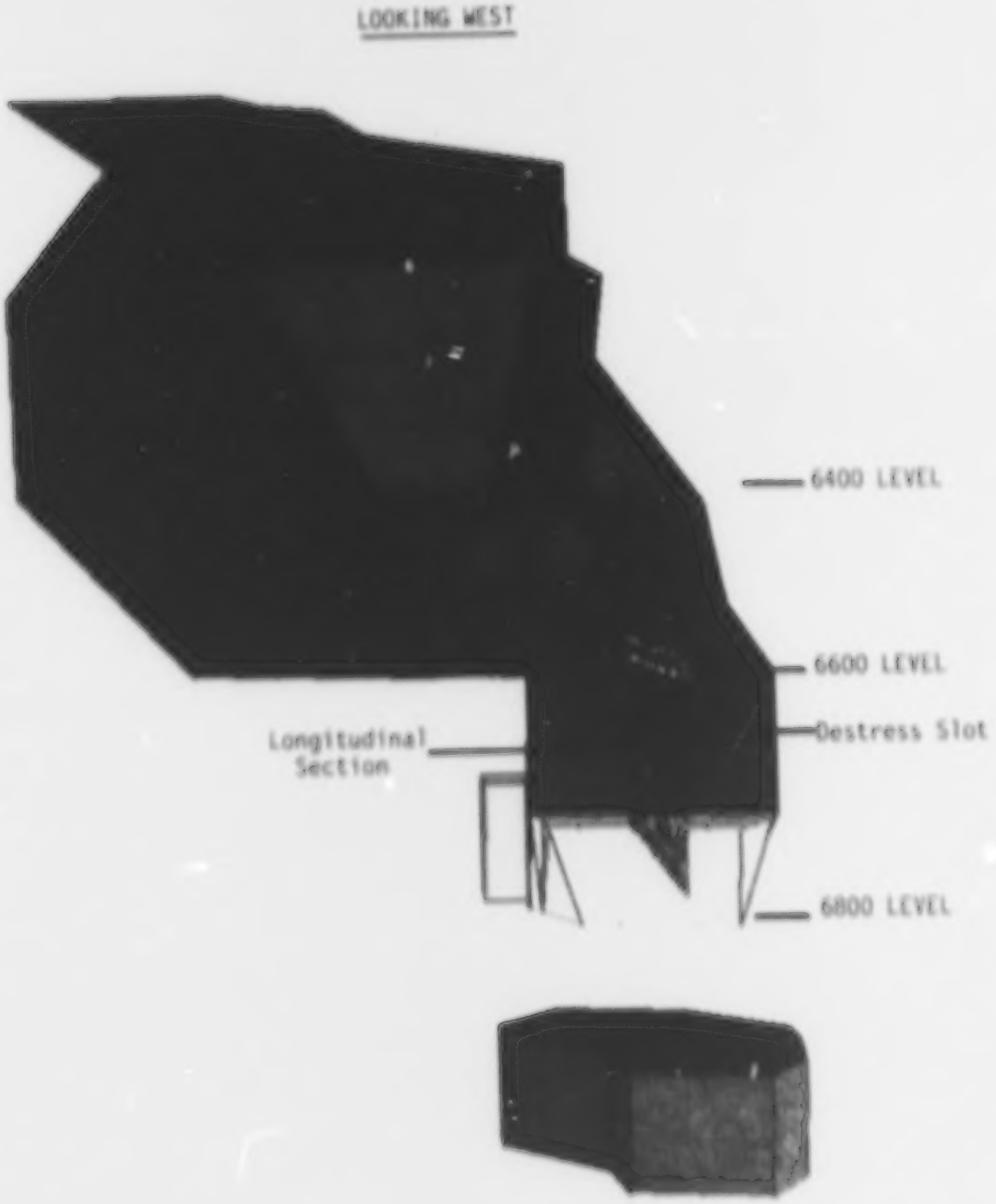

Figure 5-4 Location of Longitudinal Section for FLAC Modelling

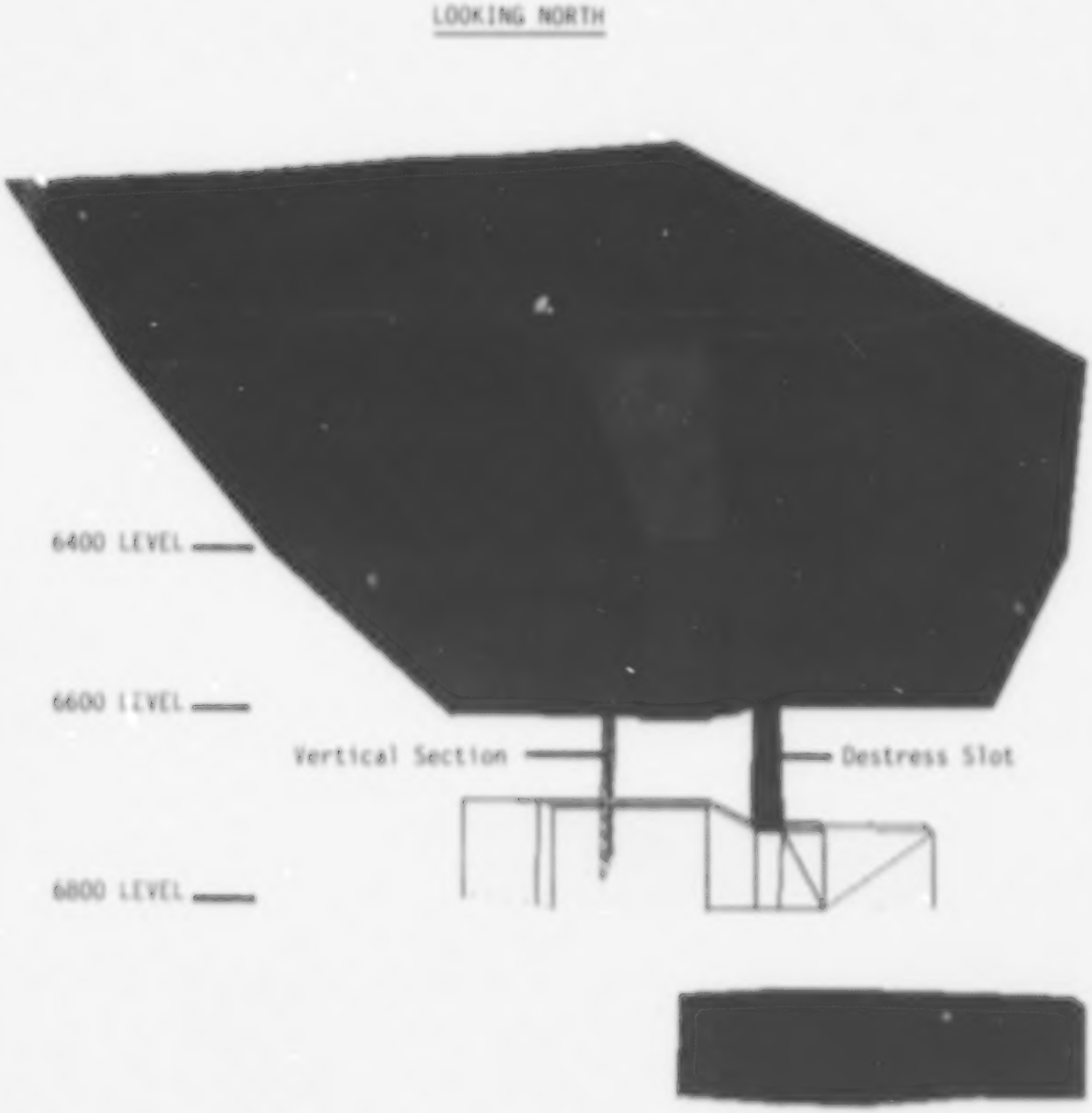

Figure 5-5 Location of Vertical Section for FLAC Modelling

5.3.5.1 Level Plan Model Geometry

The plan section geometry, which is a simplification of the ore outline on the 6650 level, is represented with the FLAC model in Figure 5-6. Although the actual strike length of the ore zone at the 6650 level is 175 metres (575 feet), only a narrow region close to the destress slot was modelled.

The overall length of the destress slot, in the plan section, is 66 metres (216.5 feet); this is the actual distance of the ore zone from the hangingwall to the footwall. The width of the slot varies from 4.5 metres at the 6600 level to 7.6 metres at the 6700 level. The width of the slot at mid-height of the ore block, 6650 level, is approximately 6 metres. The dimensions of each of the destress slot mining panels, in plan section, are summarized in Table 5-5.

Destress Slot-Panel Number	Width in metres (feet)	Length in metres (feet)
1	6.0 (19.7)	12.0 (39.4)
2	6.0 (19.7)	12.0 (39.4)
3	6.0 (19.7)	12.0 (39.4)
4	6.0 (19.7)	12.0 (39.4)
5	6.0 (19.7)	16.0 (52.5)

Table 5-5 Panel Dimensions in the Destress Slot

Six VRM panels were extracted following mining of the five panels in the destress slot. On plan, the VRM panels extend to a combined distance of 27 metres to the east of the destress slot, along the strike of the ore zone. The dimensions, in plan section, of the six VRM panels adjacent to the destress slot are listed, Table 5-6.

VRM Panels-Panel Number	Width in metres (feet)	Length in metres (feet)
1	12.0 (39.4)	12.0 (39.4)
2	12.0 (39.4)	12.0 (39.4)
3	12.0 (39.4)	12.0 (39.4)
4	15.0 (49.2)	12.0 (39.4)
5	12.0 (39.4)	12.0 (39.4)
6	12.0 (39.4)	12.0 (39.4)

Table 5-6 VRM Panel Dimensions, in Plan Section

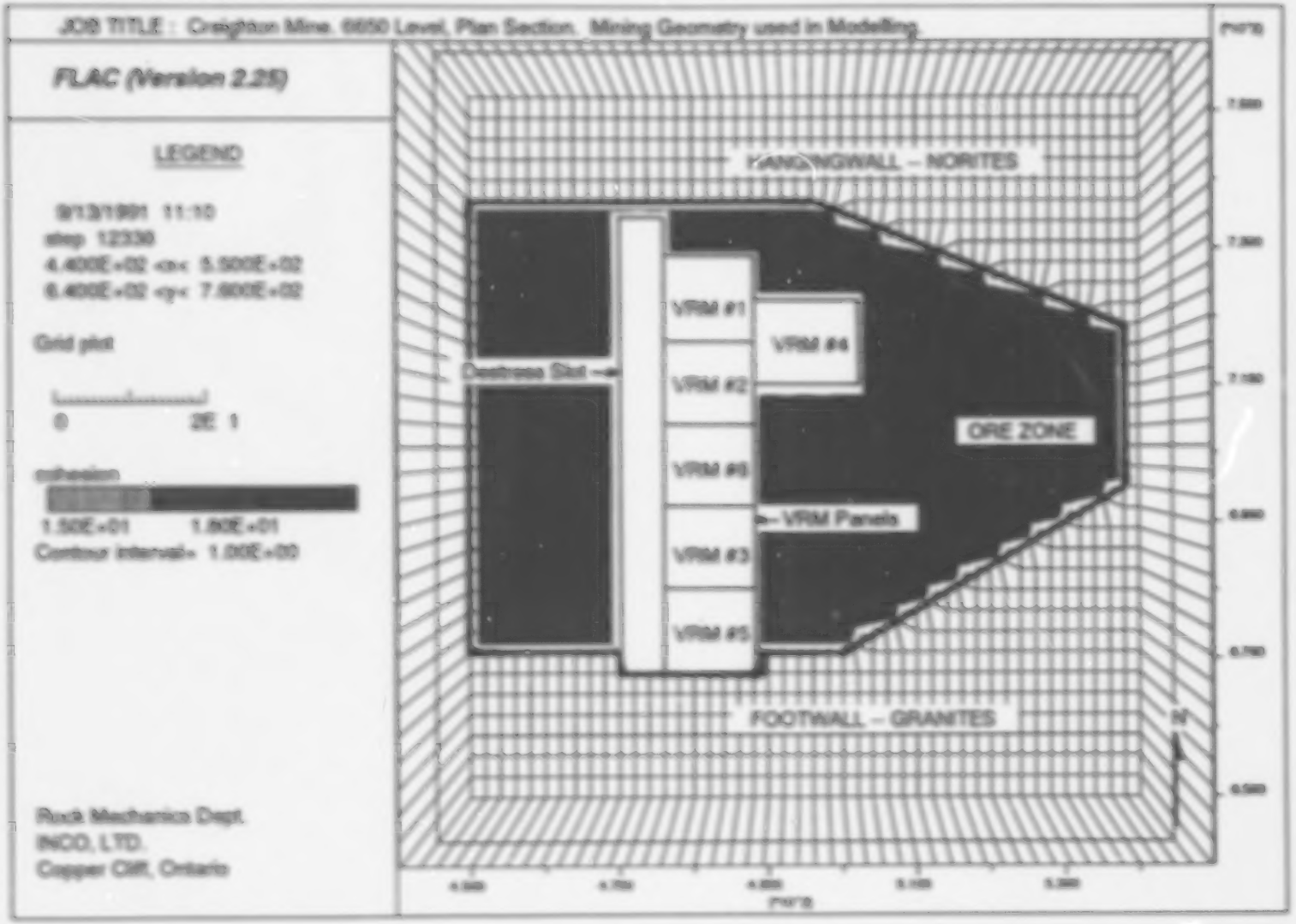

Figure 6-6 FLAC Modelling: Level Plan Geometry

5.3.5.2 Longitudinal Section Model Geometry

A longitudinal section through the entire Creighton Mine encompasses a tremendously large area. In either two- or three-dimensions, this is a extremely large problem area to model.

In the case of the two-dimensional FLAC modelling there is a loss of accuracy as the grid zones become coarser in order to encompass a larger problem area. A smaller region of the ore body is easier to model with the FLAC program and, at the same time, a more accurate set of results can be obtained with the smaller grid zones. For this reason of accuracy, a finely discretized grid is needed in the crown pillar region. However, the question as to the appropriate overall size of the FLAC longitudinal model is to be determined.

A longitudinal model, which simulates *only* the mining in the 6600-6700 Ore Block, does not provide reasonable results in the crown pillar since the influence of the upper and lower mining regions are not taken into account within the model. Because the upper and lower mining activity has a large effect on the crown pillar area, both the 6400-6600 Ore Block and the 6700-6800 Ore Block have been incorporated into the longitudinal model along with the 6600-6700 area of interest. This particular modelling geometry allows for some of the mining-induced stress effects to be initialized within the model prior to the extraction of the 6600-6700 Ore Block. Furthermore, the simulation of the previous mining provides greater accuracy with the results in the crown pillar region.

The FLAC longitudinal section used in the calibration modelling is a simplified representation of the ore zone and the mining areas. The mining geometry is depicted with the FLAC model in Figure 5-7.

It should be noted that this longitudinal section is a poor choice for two-dimensional modelling due to the lack of plane-strain conditions. Firstly, the two-dimensional simulation of the mining is a worst-case mining scenario since the model assumes the mining excavations to be infinitely long in the z-direction (into the page). Additionally, the length of each of the mining blocks, along strike of the ore body, is quite extensive while the ore geometry itself is not uniform. These two geometrical factors invalidates the assumption of plane-strain conditions with this 2D model. Nevertheless, this model has been used in the calibrations, and any erroneous results, due to the un-met plane strain conditions, will be noted.

The longitudinal section model does not take into account the mining of the VRM panels nor the destress slot. Unfortunately, the mining of the VRM panels and the destress slot, in a 2D longitudinal model, does not allow for a close approximation of the actual underground stress regime. For this reason, only the 4300 Ore Block mining was simulated in this model for calibration with the crown pillar failure.

Figure 5-7 FLAC Modelling: Longitudinal Section Geometry

A description of each of the ore blocks represented in the longitudinal section is provided:

6400-6600 Ore Block- The approximate length of the ore body, along strike, ranges from 265 metres (870 feet) at the 6400 level to 165 metres (540 feet) at the 6600 level. A mechanized cut-and-fill mining method was used (using transverse rib pillars as support).

6700-6800 Ore Block- The geometry of this ore block is uniform; there is an average strike length of 163 metres (535 feet) on both the 6700 and 6800 levels. This block was mined using the cut-and-fill method with transverse rib pillars.

4300 Ore Block- This ore block is located on the west end of the ore body, above the 6700-6800 Ore Block. The geometry of this ore block is uniform, and the mining was carried out using mechanized cut-and-fill.

A summary of the mining dimensions for each of the ore blocks, represented in the longitudinal model (refer to Figure 5-7), is provided in the Table 5-7.

	Length, x-direction in metres (feet)	Height, y-direction in metres (feet)
6400-6600 Ore Block	250 (820)	54.8 (180)
6700-6800 Ore Block	160 (525)	24.0 (78.9)
4300 Ore Block	120 (393)	15.2 (50.0)

Table 5-7 Mining Dimensions, Longitudinal Section

5.3.5.3 Vertical Cross-Section Model Geometry

As with the longitudinal model, a vertical cross-section of Creighton Mine is a tremendously large area, and any attempt to model the cross-section of the entire ore body would require a very large FLAC grid. In order to provide reasonable run-times with the large grid, the zones would need to be quite coarse, and the model results, using such a coarse grid, would only provide very vague details within the comparatively small crown pillar region.

Ideally, a large and finely discretized 2D model, which has fast run-times, would be the best choice for modelling this area. Unfortunately, a proven two-dimensional plasticity model which is capable of analysing a large area, in great detail, and with fast turn-around times is not available.

As an alternative, the "smaller" crown pillar region was modelled with a more finely-discretized grid whereby greater detail of the stresses, displacements, and the extent of the failure associated with the mining was obtained. This finer grid is more suitable because the results in the crown pillar region can be more easily and more accurately calibrated with the field site data.

The crown pillar region, although far from plane-strain conditions, was modelled in cross section with the inclusion of some of the upper and lower mining areas: the 6400-6600 Ore Block and the 6700-6800 Ore Block, respectively. The simulation of this previous mining is necessary for more accurate results in the crown pillar area. This cross-section, which includes the mining between 6400 level to 6800 level, allows for the initialization of some of the pre-slot mining effects prior to the simulation of the crown pillar mining.

The extensive mining above 6400 level could not be included in this model due to the gross run-times for such a large model; obviously, this mining in the upper regions of the mine would have also had a significant effect on the crown pillar ore block.

A examination of the ore zone from the 6400 level to the 6800 level in cross-section yields a complex geometry. The western part of the ore zone above 6600 level is much wider, from hangingwall to footwall, than the eastern section and this variation in geometry is not a favourable condition for two-dimensional modelling. The calibration model is based only on the western side of the zone since this area has been well-documented regarding the actual failure of the crown (at the 90-foot thickness). The information on the failure of the crown has been used to calibrate the model.

The resulting cross-sectional geometry, from 6400 level to 6800 level, is represented with the FLAC model in Figure 5-8. A summary of the mining dimensions for each of the mining steps is provided in Table 5-8.

Figure 5-6 FLAC Modelling: Vertical Section Geometry

	Width, x-direction in metres (feet)	Height, y-direction in metres (feet)
6400-6600 Ore Block	121.9 (400)	54.8 (180)
6700-6800 Ore Block	61 (200)	26.5 (87)
4300 Ore Block	61 (200)	15.24 (50) -in 10 foot slices

Table 5-8 Dimensions of the Mining Blocks in the Vertical Cross-Section Model

The mining blocks, incorporated within the cross-sectional model, are further described:

6400-6600 Ore Block- The ore block, in vertical cross section, is fairly uniform on the western part of the ore body. The approximate width of the ore zone in this region, from footwall to hangingwall, is 137 metres (450 feet).

6700-6800 Ore Block- The geometry of this ore block is also uniform; the average width (from footwall to hangingwall) is 60.9 metres (200 feet) on both the 6700 and 6800 levels.

4300 Ore Block- The mining above 6700 level in the western region of the ore zone is referred to as the 4300 Ore Block. The average width of the zone, from the footwall to the hangingwall is 60 metres (200 feet).

5.3.4 Sequence of Extraction

Due to the three different geometries used in the calibration modelling, the sequence of ore extraction is unique for each model. All three mining sequences, however, were chosen such that they each mimic the actual underground mining sequence as much as possible. The details of the mining sequences for each of the models are outlined within the following subsections.

5.3.6.1 Plan Section Mining Sequence

The mining sequence used for the extraction of the 6600-6700 ore block is represented in the plan section with the FLAC model, shown in Figure 5-9. The overall mining sequence is as follows: the destress slot is first extracted using five mining steps (vertical panels), and then the six VRM panels are mined. The mining sequence is summarized in Table 5-9. The modelling has been set-up with these eleven mining steps in order to best reflect the underground mining history.

step 1-5	- mining of destress slot, 5 panels - backfilling of slot panels with hydraulic fill
step 6-11	- VRM mining, 6 panels - backfilling of VRM panels with hydraulic fill

Table 5-9 Plan Section Model, Mining Sequence

5.3.6.2 Longitudinal Section Mining Sequence

The mining sequence used for the longitudinal modelling is represented with the FLAC model in Figure 5-10. The corresponding mining sequence is outlined in Table 5-10.

step 1	- mining of the upper ore block between 6400 level and 6600 level - backfilling of this area using a stiff fill
step 2	- mining of the lower ore block between 6700 level and 6600 level - backfilling of this area using a stiff fill
step 3-4	- mining of the 6300 ore block (west of the destress slot) above the 6700 level - backfilling of this area using a stiff fill

Table 5-10 Longitudinal Section Model, Mining Sequence

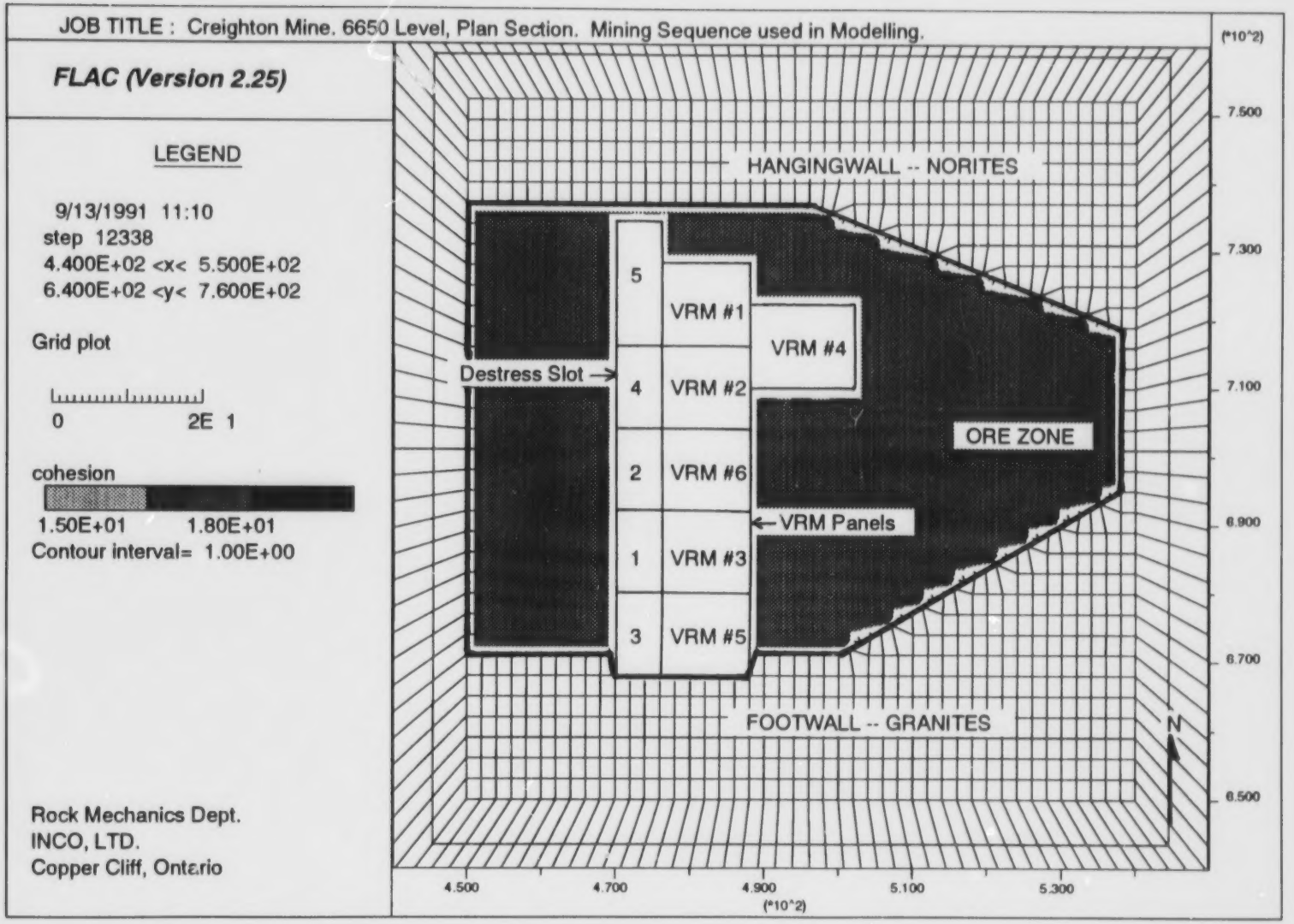

Figure 5-9 FLAC Modelling: Plan Section Mining Sequence

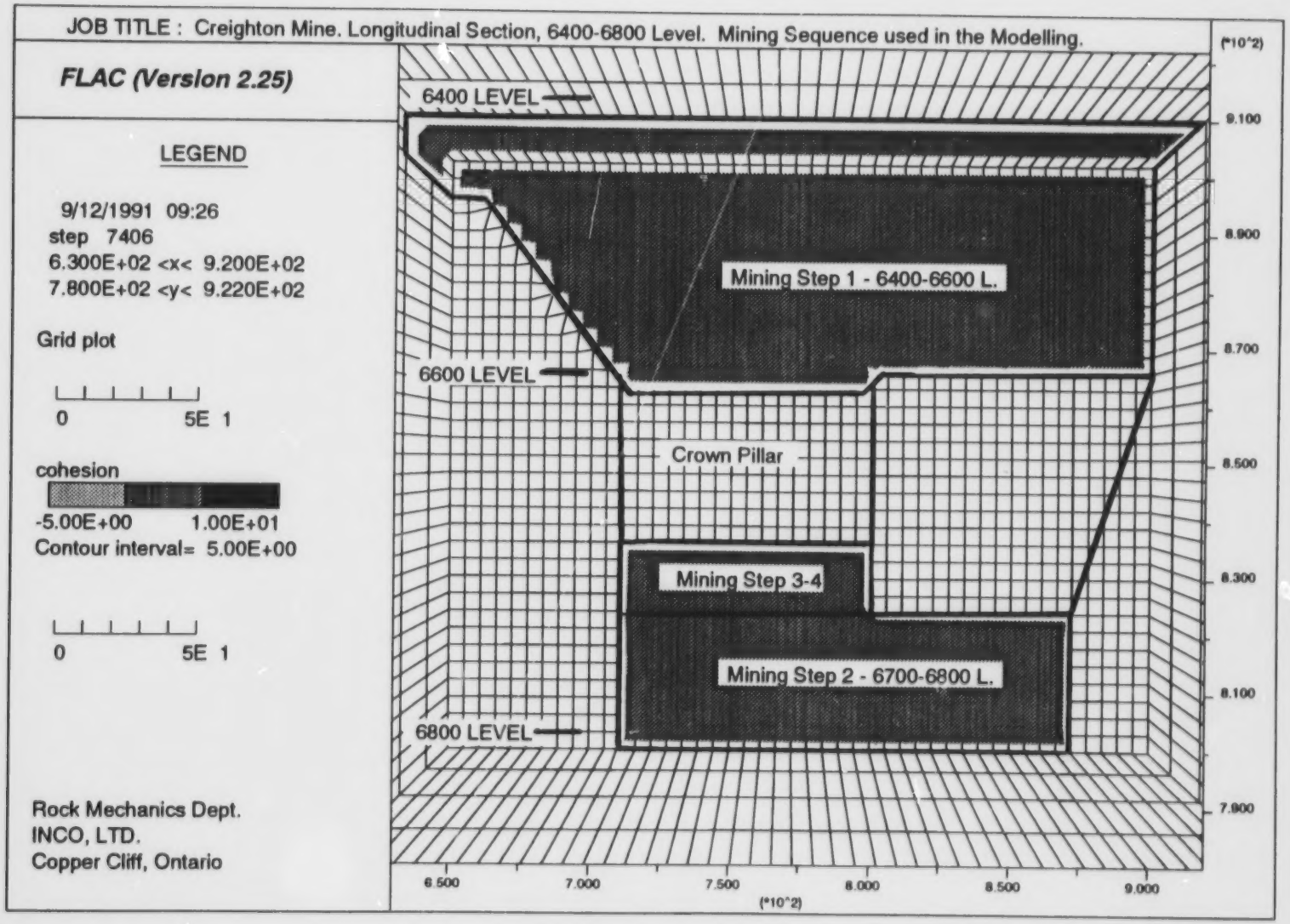

Figure 5-10 FLAC Modelling: Longitudinal Section Mining Sequence

5.3.6.3 Vertical Cross Section Mining Sequence

The mining sequence used for the cross-section modelling is represented with the FLAC model, shown in Figure 5-11. For the purpose of calibrating the model, with the crown pillar failure at a thickness of 90 feet, the following mining sequence was utilized, Table 5-11.

step 1	- mining of the upper ore block (6400-6600 level) - backfilling using stiff fill
step 2	- mining of the lower ore block (6700-6800 level) - backfilling using stiff fill
step 3-7	- mining from 6700 to 6600 level (4300 ore block), using 3 metre (10 foot) vertical slices, on the west side of the destress slot - backfilling using stiff fill

Table 5-11 Mining Sequence for the Cross-Section Model

After the upper and lower mining blocks had been completely excavated in the model, the mining commenced in the 4300 Ore Block. The cross-sectional model simulates the 4300 mining with a progressive series of vertical slices, each being 10 metres in height.

The cross-sectional model does not take into account the mining of the destress slot on the eastern section of the ore zone. Only the assumed failure of the western section of the crown pillar has been used in the calibration of this model.

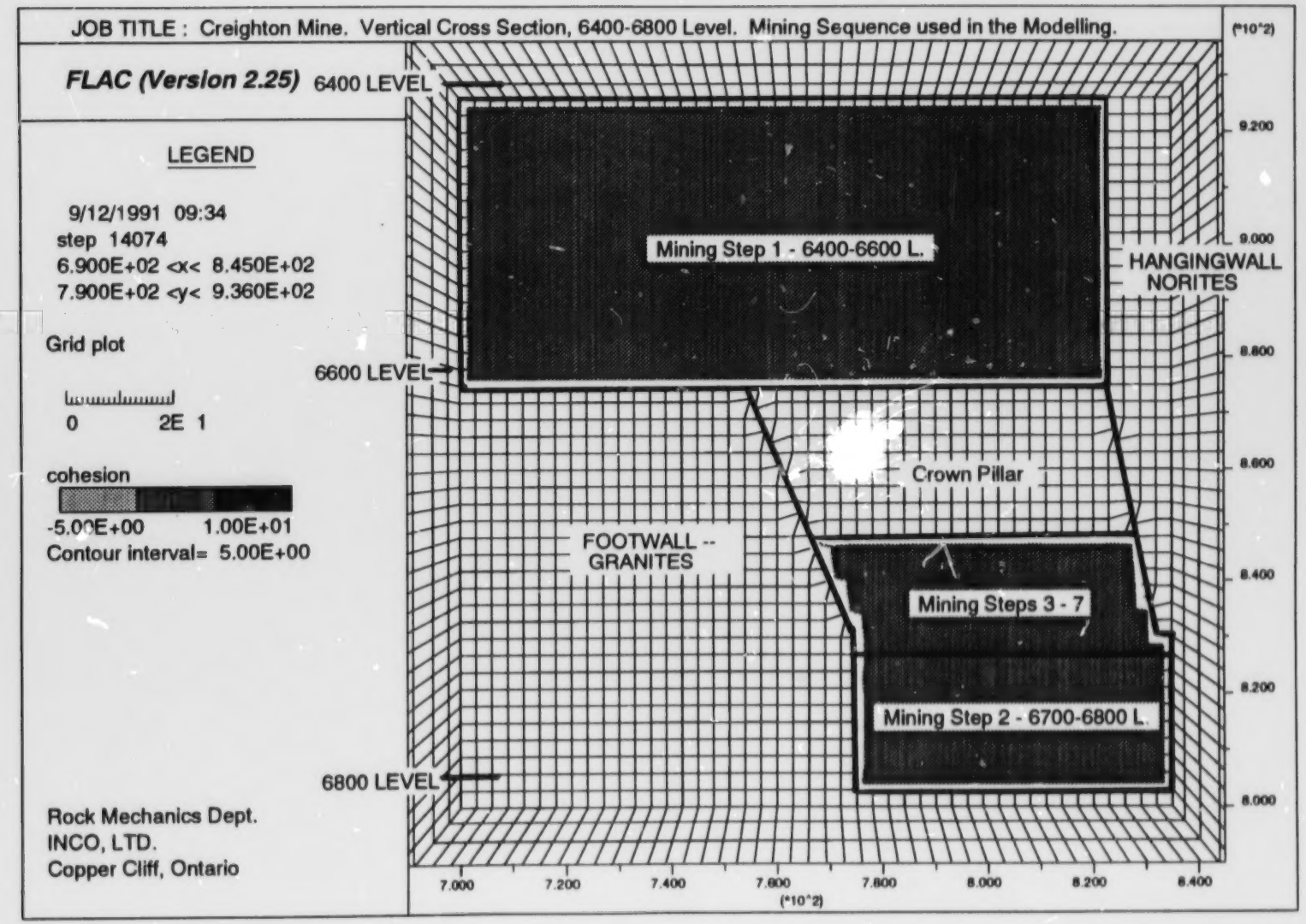

Figure 5-11 FLAC Modelling: Vertical Section Mining Sequence

5.4 Results

The 2D FLAC models were each calibrated using the information from the field instrumentation. As well, the models were calibrated using the documented information regarding the ground conditions within the case study site. The resulting set of input parameters for the three rock types are summarized in Table 5-12. These rock properties provided FLAC results that were representative of the actual observed ground conditions and the observed field data for all three modelling sections through the case study site.

	Rock Properties:
Ore Zone	E = 68.0 GPa ν = 0.25 Bulk Modulus = 45300 MPa Shear Modulus = 27200 MPa Density = 3000 kg/m^3 Cohesion = 22 MPa ϕ = 35°
Norites	E = 79.0 GPa ν = 0.29 Bulk Modulus = 62700 MPa Shear Modulus = 30620 MPa Density = 2900 kg/m^3 Cohesion = 30 MPa ϕ = 30°
Granites	E = 55.0 GPa ν = 0.25 Bulk Modulus = 36700 MPa Shear Modulus = 22000 MPa Density = 3000 kg/m^3 Cohesion = 20 MPa ϕ = 35°

Table 5-12 Resulting Input Parameters for the FLAC Models

The determined parameters for simulating the backfill material are outlined in Table 5-13; these backfill properties were used in all three of the FLAC models for simulation of hydraulic fill.

Cemented Hydraulic Backfill-
Resulting Input Parameters:

Elastic Properties:

E = 23.6 MPa
ν = 0.20
Bulk Modulus = 13 MPa
Shear Modulus = 11 MPa
density = 1800 kg/m^3

Plastic Properties:

ϕ = 33°
C_o = 0.25 MPa
cohesion = 0.067 MPa

Table 5-13 Resulting Hydraulic Backfill Properties for the FLAC Modelling

In the case of the longitudinal modelling and the vertical cross-section modelling, property values representing the combination of rib pillars and hydraulic backfill were required. The resulting set of input parameters are summarized in the following Table 5-14. The actual determination of these values are outlined within the succeeding subsections discussing the specific modelling results.

Backfill/Rib Pillar Combination-
Resulting Input Parameters:

Elastic Properties:

E = 11.0 GPa
ν = 0.15
Bulk Modulus = 5200 MPa
Shear Modulus = 4800 MPa
density = 2000 kg/m^3

Plastic Properties:

ϕ = 30°
C_o = 20 MPa
cohesion = 5.8 MPa

Table 5-14 Resulting FLAC Input Properties for the Combined Effect of Hydraulic Backfill and Rib Pillars

5.4.1 Plan Section Modelling Results

Before the specific modelling results were analyzed, the validity of using a two-dimensional program to simulate mining in a plan section was assessed.

A cursory overview of the 6600-6700 ore block indicated a fairly uniform ore geometry which, without any other mining in the vicinity, could be modelled in plan section using the assumption of 2D plane-strain conditions. The destress slot is, essentially, a long thin member extending over a vertical distance of 42 metres (140 feet). This slot was mining using small VRM-type panels which stretch over a comparatively extensive height. Initially the model behaved in plane-strain; however, as the slot was increasingly enlarged from hangingwall to footwall, the plane-strain conditions were reduced. Once the final VRM panels were removed, the plane-strain relationship was entirely diminished. This reduced validity in plane-strain conditions is due to the pre-slot mining. Both the extensive mining above 6600 level and the mining below 6700 level have an obvious effect on the ore block; these effects could not be taken into account with the plan section model.

From the analysis of the validity of the 2D plan section modelling, it was reasonable to assume that the initial simulation of the mining would yield results representative of the underground conditions. It was also reasonable to assume that, as the simulated mining was extended into the later stages with the VRM removal, the modelling results would be somewhat less representative. Based on these assumptions, the initial modelling results were closely calibrated with the field site data, while less emphasis was placed on matching field data with modelling results in the later stages of mining simulation. The actual details of the calibration of the modelling results are provided, first with the destress slot then the VRM mining simulations.

Initially the destress slot was extracted in five mining steps. For each mining step, the predicted zone of failure surrounding the slot was matched to the field site data. The series of mining steps and corresponding rock mass failure, as predicted from FLAC, are depicted in Figures 5-12 (a,b,c,d,e). Figure 5-12 (e) corresponds to the rock mass state at the completion of the destress slot mining. Note that any element within the FLAC grid that is indicated as being "at yield" is considered to be failed. The elements that are indicated as being "elastic, at yield in the past" are also areas of failed, broken-up ground.

Prior to the mining of the destress slot, no instrumentation was i place and no borehole camera work had been conducted in order to assist in the model calibrations. At the end of the destress slot mining, the instrumentation was installed. Also, the extent of the failure envelope was determined from borehole camera work; the rock mass adjacent to the destress slot was broken-up and failed over a distance equal to approximately 1 width of the destress slot (6 m).

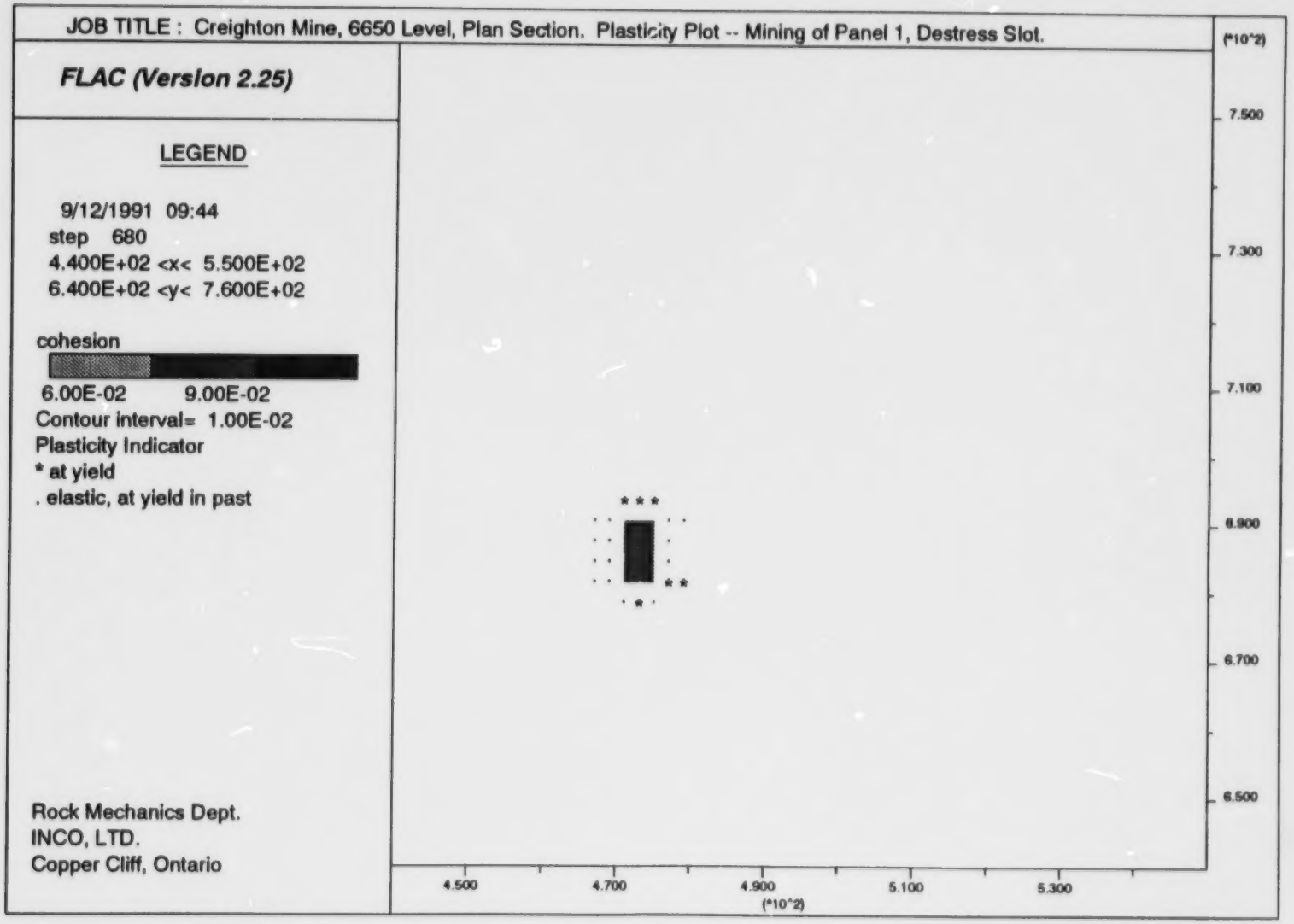

Figure 5-12(a) FLAC Model, Plan Section
Destress Slot, Panel 1 Mined: Plasticity Plot

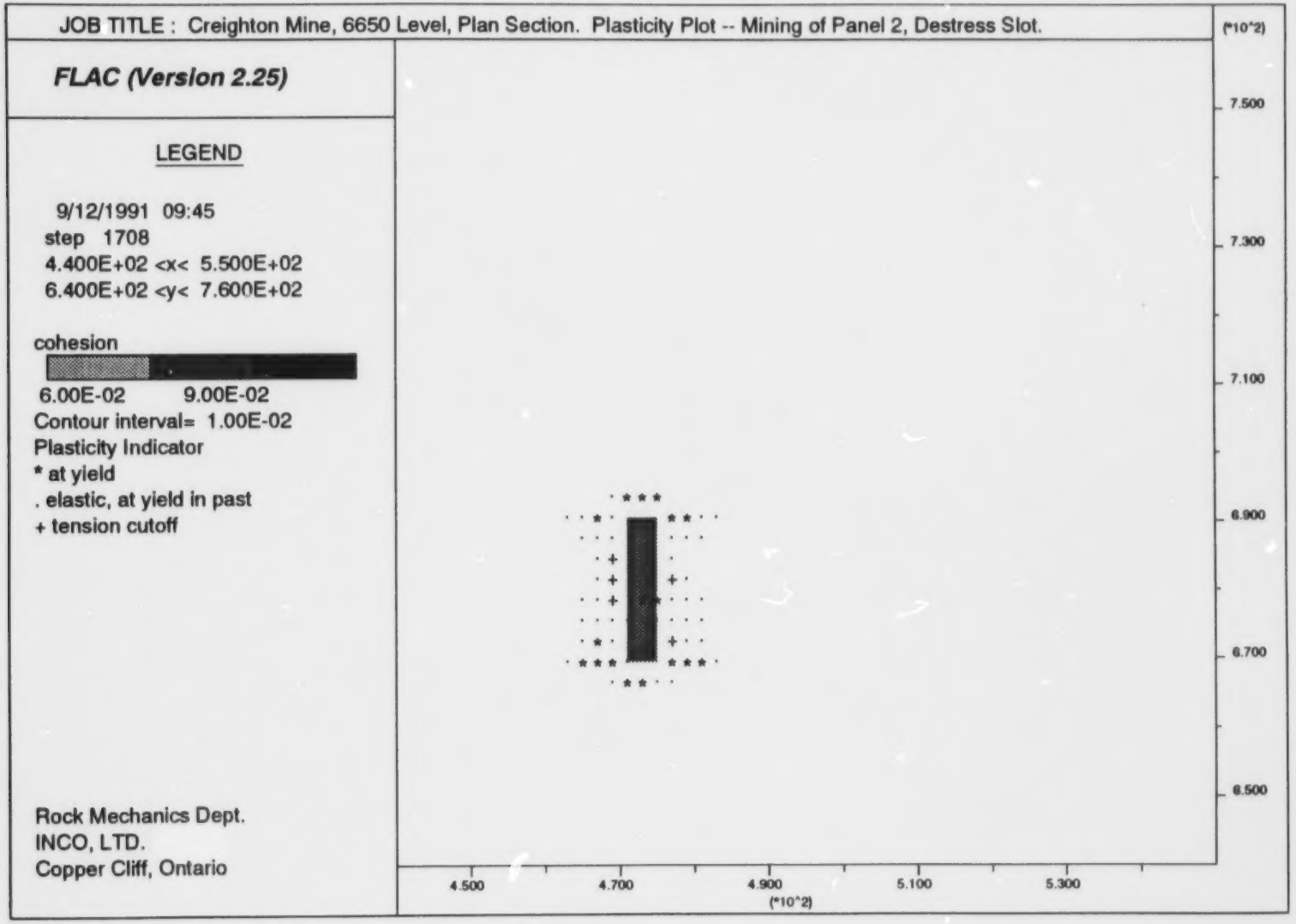

Figure 5-12(b) FLAC Model, Plan Section
Destress Slot, Panel 2 Mined: Plasticity Plot

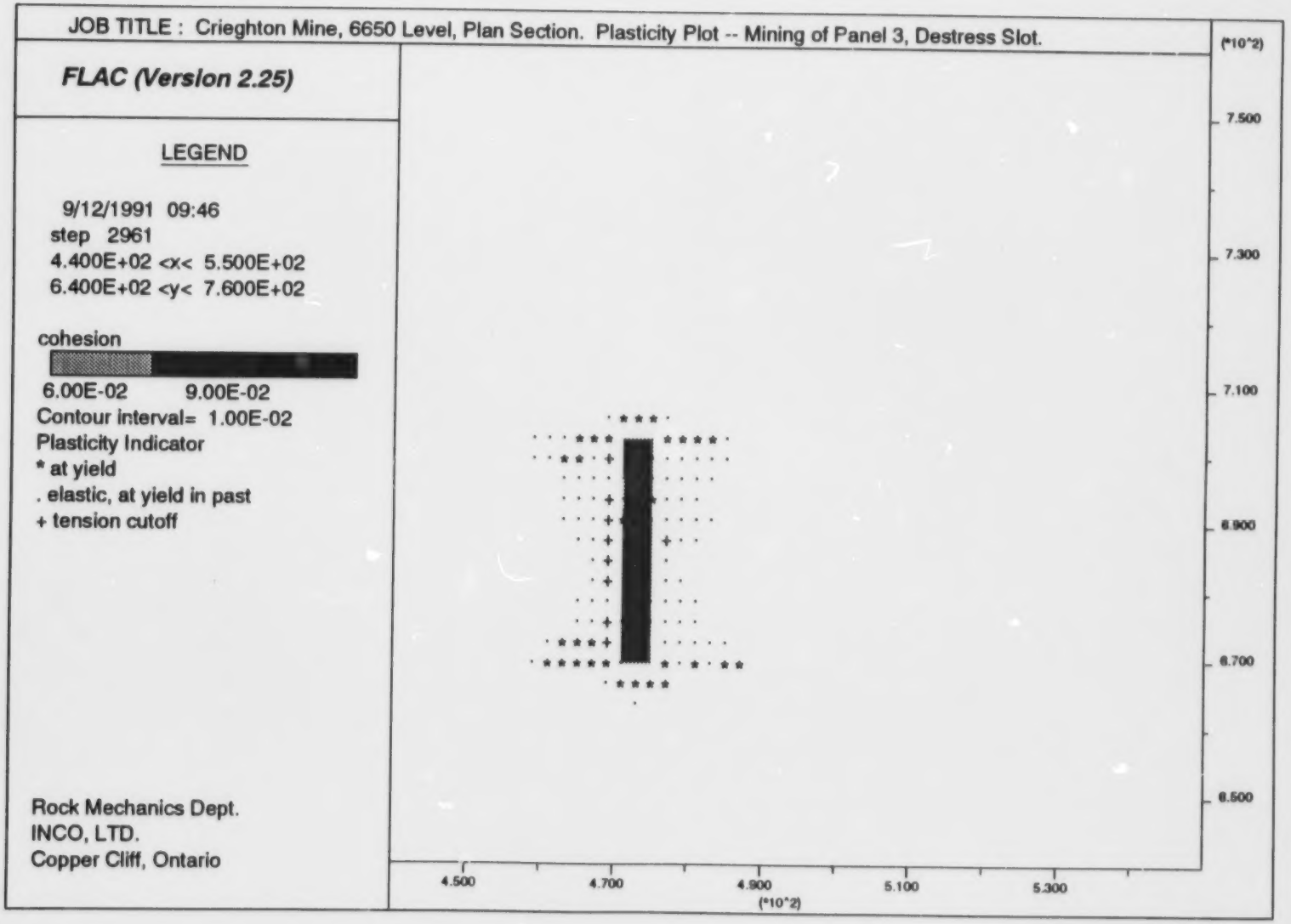

Figure 5-12(c) FLAC Model, Plan Section
Destress Slot, Panel 3 Mined: Plasticity Plot

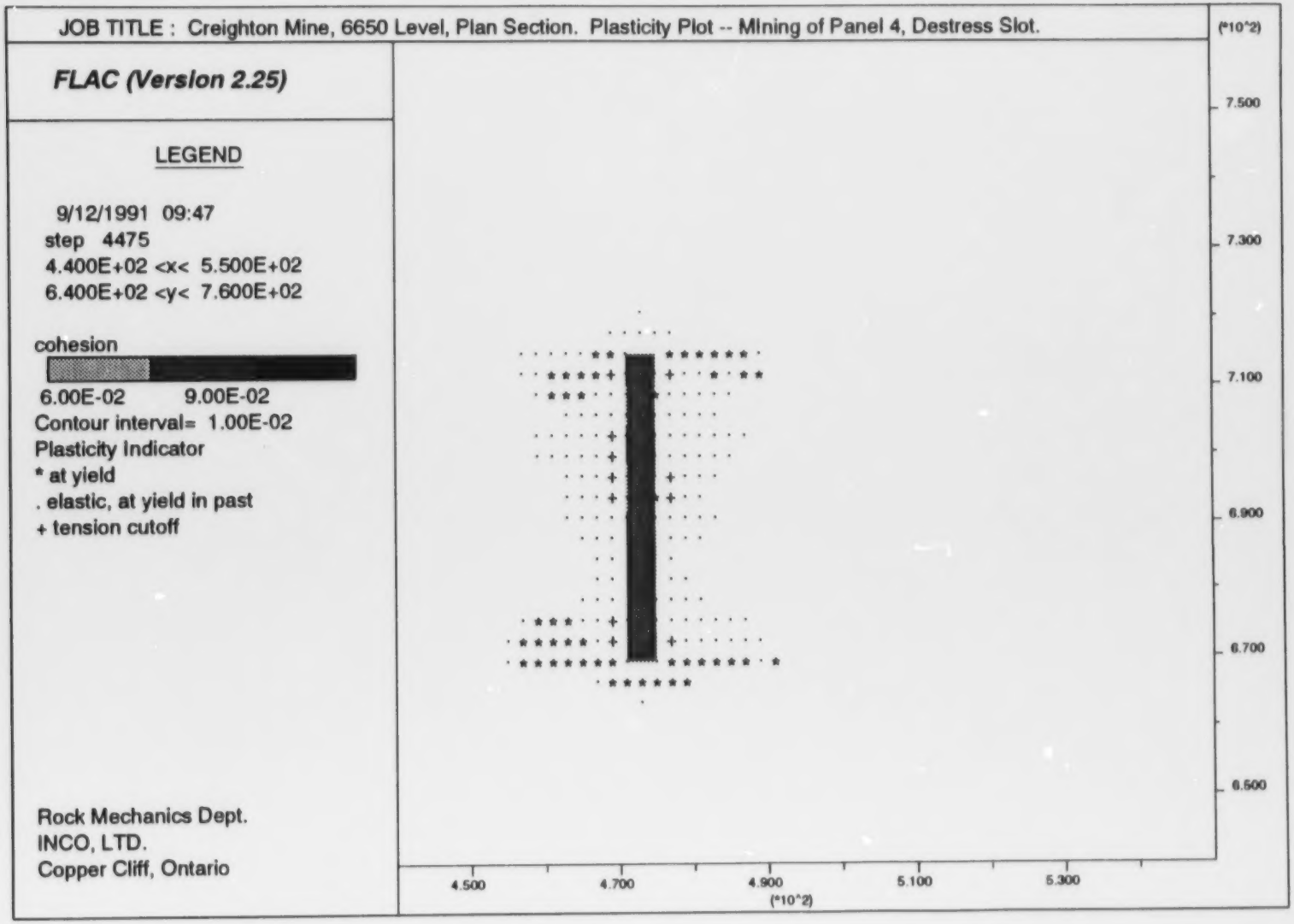

Figure 5-12(d) FLAC Model, Plan Section
Destress Slot, Panel 4 Mined: Plasticity Plot

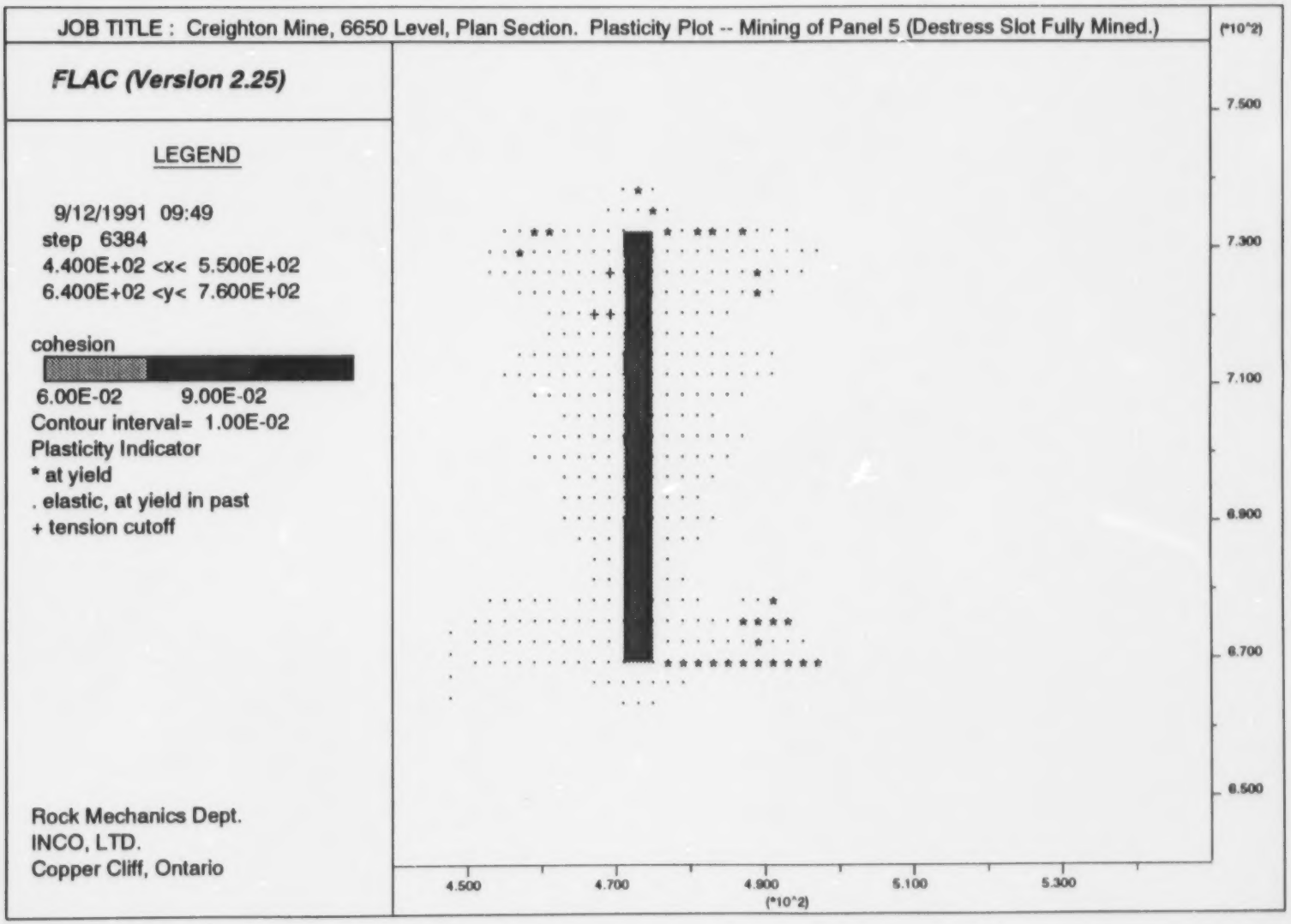

Figure 5-12(e) FLAC Model, Plan Section
Destress Slot, Panel 5 Mined: Plasticity Plot

Referring to Figure 5-12 (e), the plot indicates that the rock mass surrounding the slot is predicted as being yielded. The average extent of the plastic behaviour is approximately equal to the width of the slot; this is in agreement with the observed field data. At this point in the modelling, the FLAC results and the borehole camera data are matched exactly.

The predicted stress state from the FLAC model, at the end of the destress slot mining, is shown in Figures 5-13 (a,b). The average principal stress (sigma 1) at the hangingwall and footwall abutments of the destress slot is 250 MPa, Figure 5-13 (a). The Sigma 2 Stress Contour Plot is depicted in Figure 5-13 (b).

The distribution and magnitude of stresses for this stage in mining was compared to results of the BEM3D, BEM2D, and 3DEC models (using identical input parameters). Both BEM3D and 3DEC predicted a maximum principal stress in the range of 200 MPa while the BEM2D and the FLAC models both predicted a slightly higher maximum principal stress of 250 MPa. Although the BEM2D model assumes a perfectly elastic medium, the modelling code was used as a comparison to the FLAC plan model; an identical BEM2D modelling geometry is represented in Figure 5-14.

The BEM2D stresses have been plotted for comparison to the FLAC stress plots. Figure 5-15 (a) represents the BEM2D Sigma 1 Plot and Figure 5-15 (b) represents the BEM2D Sigma 3 Plot. These BEM2D stress plots are nearly identical to the FLAC results. [Note that BEM2D refers to the minor stress as Sigma 3; in FLAC this stress is referred to as Sigma 2.] Additionally, a BEM2D Factor of Safety Plot has been produced at the same mining stage, Figure 5-15 (c).

The historical data on the behaviour of the rock mass at this stage in the mining indicated a tremendous, and sudden, inward movement of the walls of the destress slot. This sudden displacement was evidenced underground with damage in the hangingwall drifts close to the destress slot. The rails in one of the drifts were buckled vertically approximately 9 cm due to the inward movement.

A comparison with the FLAC model indicates a high level of inward displacement surrounding the destress slot walls, Figure 5-16. The displacement magnitudes predicted by the FLAC model do not match the underground measurements, however, the qualitative correlation is notable.

After the destress slot mining simulations, the results of the calibrated FLAC model indicate a close correlation with both the results of other numerical models as well as with the borehole camera data. The progression to the calibration of the model with the simulation of the VRM mining has been carried-out with less emphasis on precision. For the later mining simulations, the model was calibrated to within a close approximation of the borehole camera data and the known ground conditions.

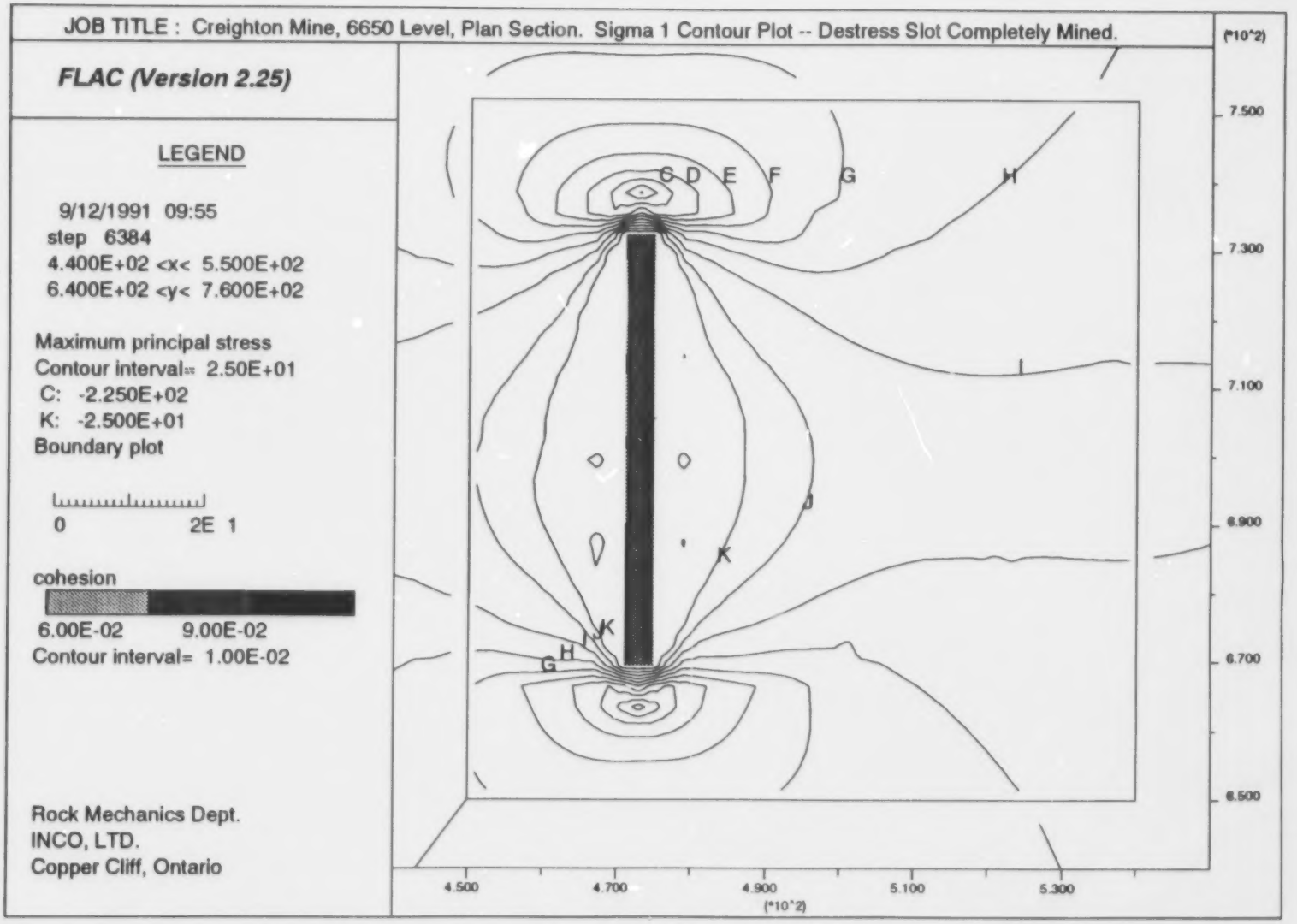

Figure 5-13(a) FLAC Model, Plan Section
Destress Slot is Mined. Sigma 1 Contour Plot.

Figure 5-13(b) FLAC Model, Plan Section
Destress Slot is Mined. Sigma 2 Contour Plot.

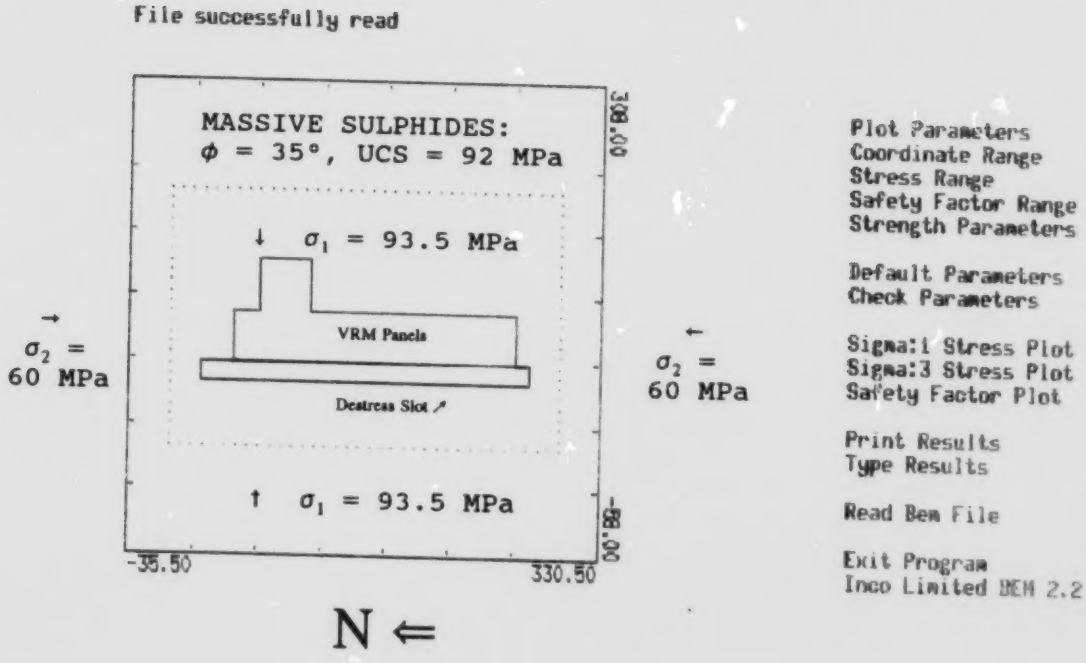

Figure 5-14 BEM2D Modelling Geometry, Plan Section

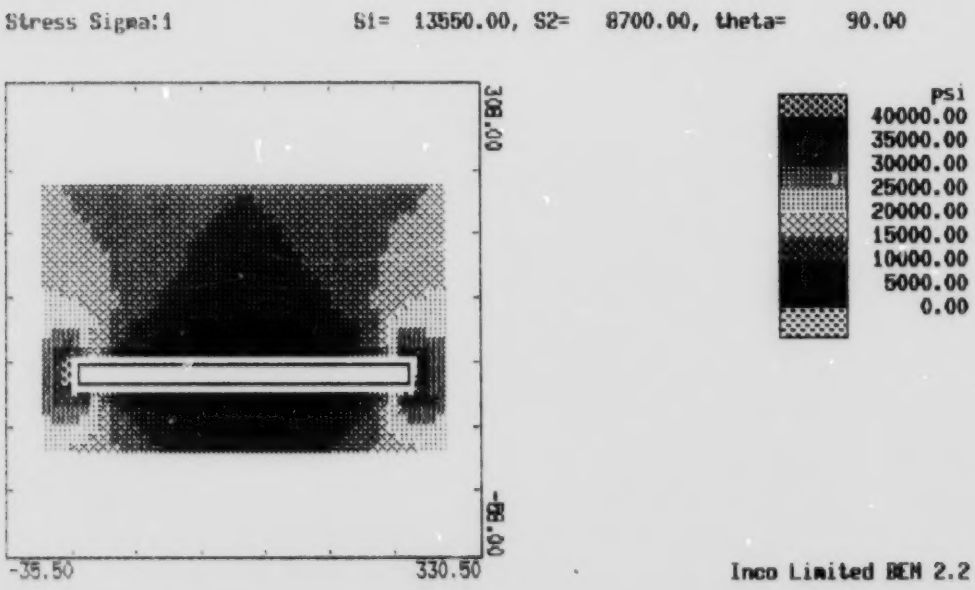

Figure 5-15(a) BEM2D Model, Plan Section Destress Slot is Mined. Sigma 1 Contour Plot.

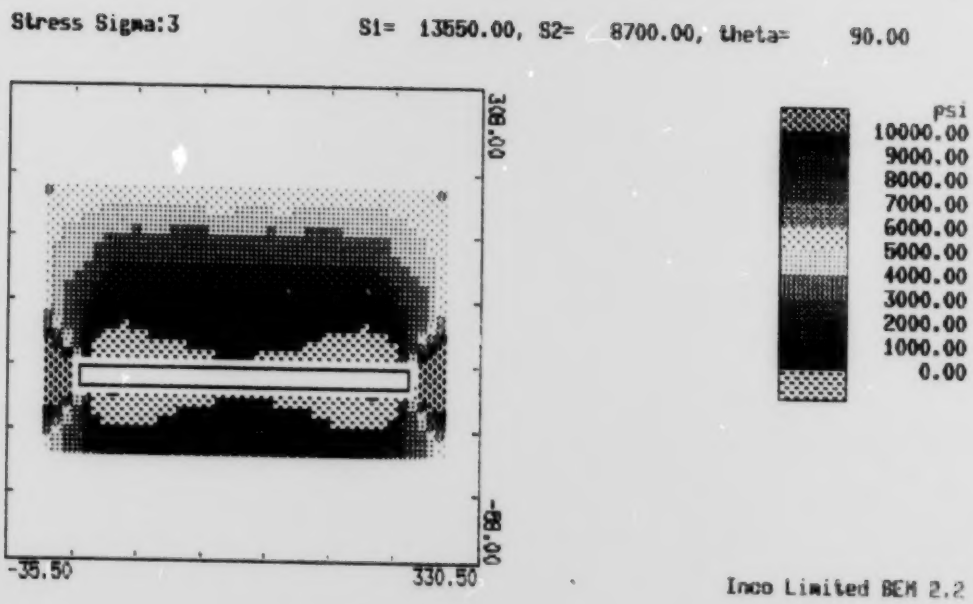

Figure 5-15(b) BEM2D Model, Plan Section
Destress Slot is Mined. Sigma 3 Contour Plot.

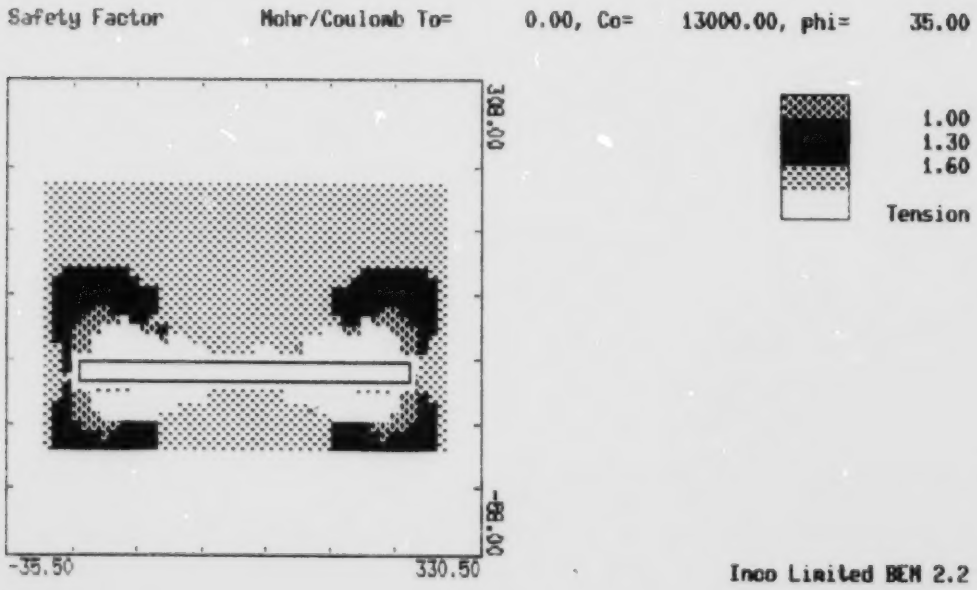

Figure 5-15(c) BEM2D Model, Plan Section Destress Slot is Mined. Factor of Safety Plot.

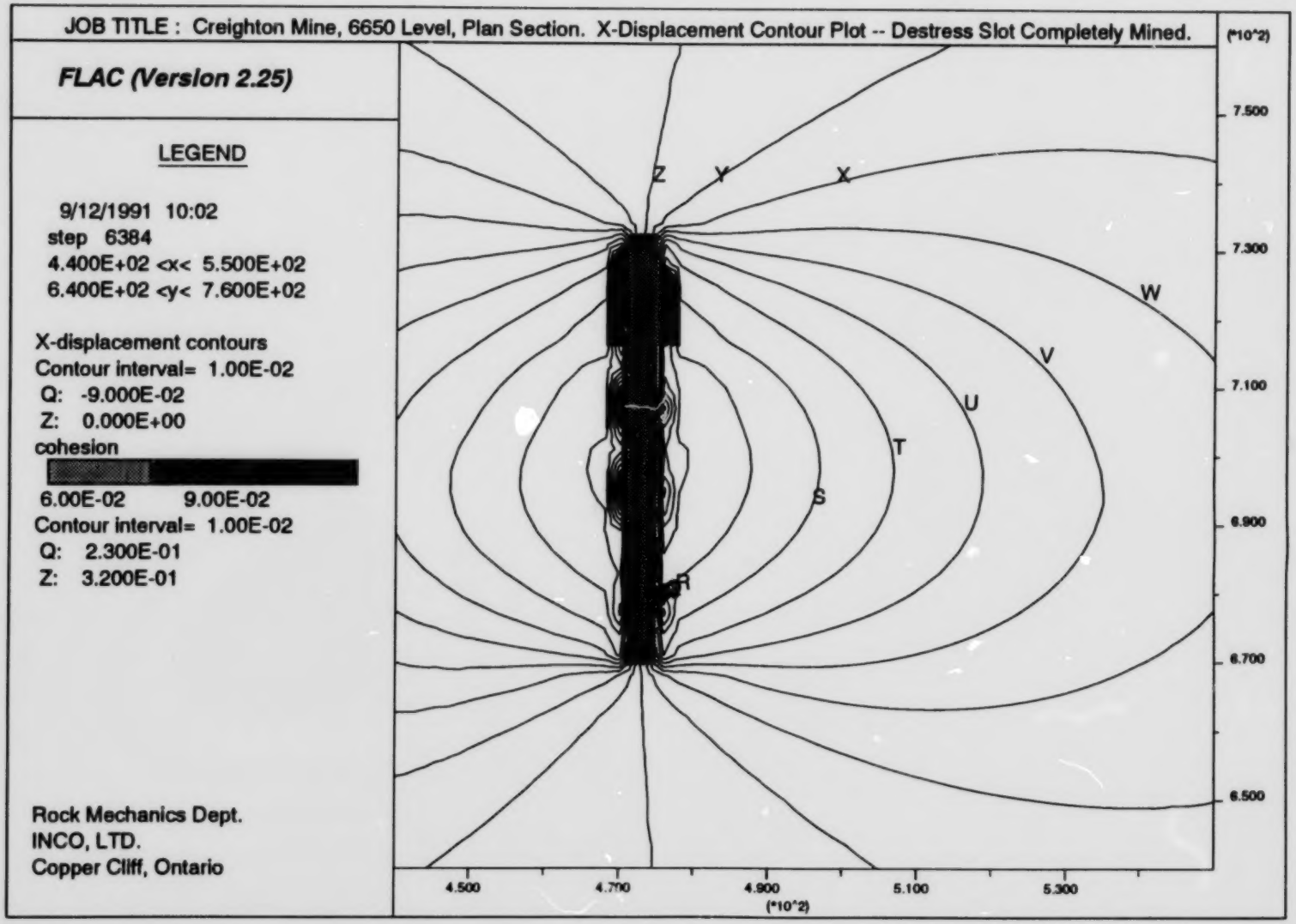

Figure 5-16 FLAC Model, Plan Section
Destress Slot is Mined. X-Displacement Contour Plot.

After mining VRM panel #1, the borehole camera work indicated a plastic zone (failure envelope) which extended passed the boundary of the VRM panel by approximately 10 to 20 feet (to the north and to the east). These results were compared to the FLAC State Plot, Figure 5-17. This plot indicates that the predicted plastic zone from the FLAC calibration modelling is within a close match to the field site data.

The mining of the next two VRM panels were examined with the FLAC model and the results indicate a progressively extending failure zone. After mining VRM panel #3, the zone of failure had again extended passed the boundary of the mining in the first row of panels by approximately 20 feet. The plasticity zones associated with the mining of these two panels are represented with the FLAC model in Figure 5-18 (mining of VRM Panel #2) and Figure 5-19 (mining of VRM Panel #3). This predicted failure zone approximates the field camera data fairly well.

Of particular interest is Figure 5-19; this plot represents the mining stage where the third VRM panel had been removed and the fourth panel was about to be drilled-off. The fourth VRM panel is located just at the outer edge of the mined area. The borehole camera data for this area was augmented with some ITH drilling information regarding the fourth VRM panel. The drillers claimed that the drilling of the first half of VRM panel #4 progressed rapidly and without difficulty. The first half of the panel refers to the holes drilled closest to the destress slot area. Conversely, the outer half of this panel was not as easy to drill, i.e., the holes furthest away from the destress slot. This outer section of the panel experienced heavy discing in the drilled holes; the drilled holes also had a tendency to squeeze before they could be loaded with blasting agents.

This drilling information indicates the exact transition from failed ground, next to the previously mined panels, and the highly stressed, in-situ rock mass at the outer half of the panel. This drilling information corresponds closely to the results of the FLAC modelling shown in Figure 5-19; this plot indicates that the inner portion of the VRM panel has undergone plastic behaviour while the outer part of the panel is still elastic and intact. This outer area of the VRM panel is also highly stressed, as depicted with the stress plots.

It is worth noting that the FLAC model, at this stage in the mining simulation, is beginning to underestimate the extent of the failure zone. This is due, in part, to the gradual loss of plane-strain conditions with the plan section model (as explained at the beginning of this subsection). Had it been possible to incorporate the upper and lower mining influence within the model, the zone of failure surrounding the VRM panels would have been larger, thereby more closely resembling the borehole camera data.

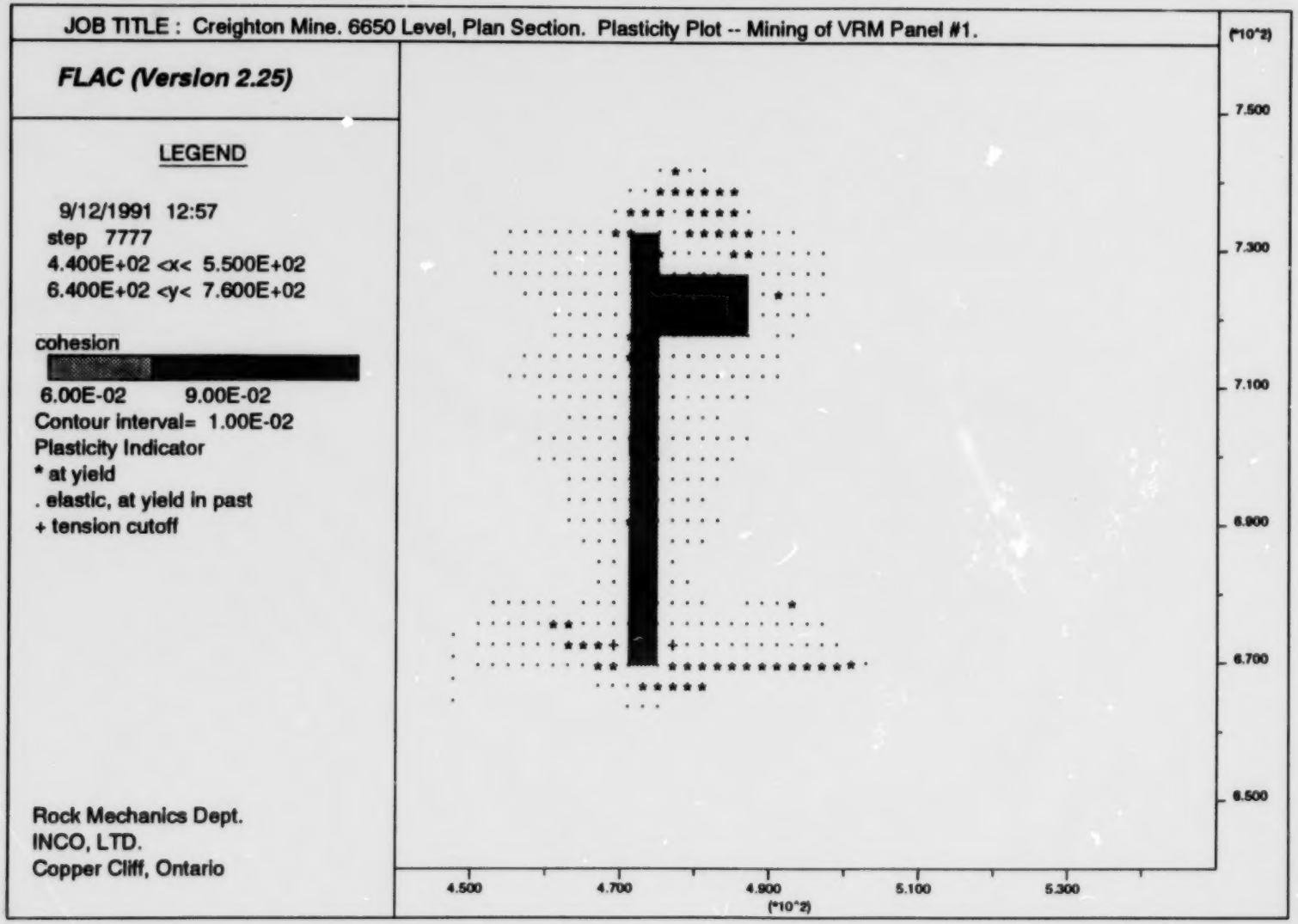

Figure 5-17 FLAC Model, Plan Section Mining of VRM Panel 1 -- Plasticity Plot

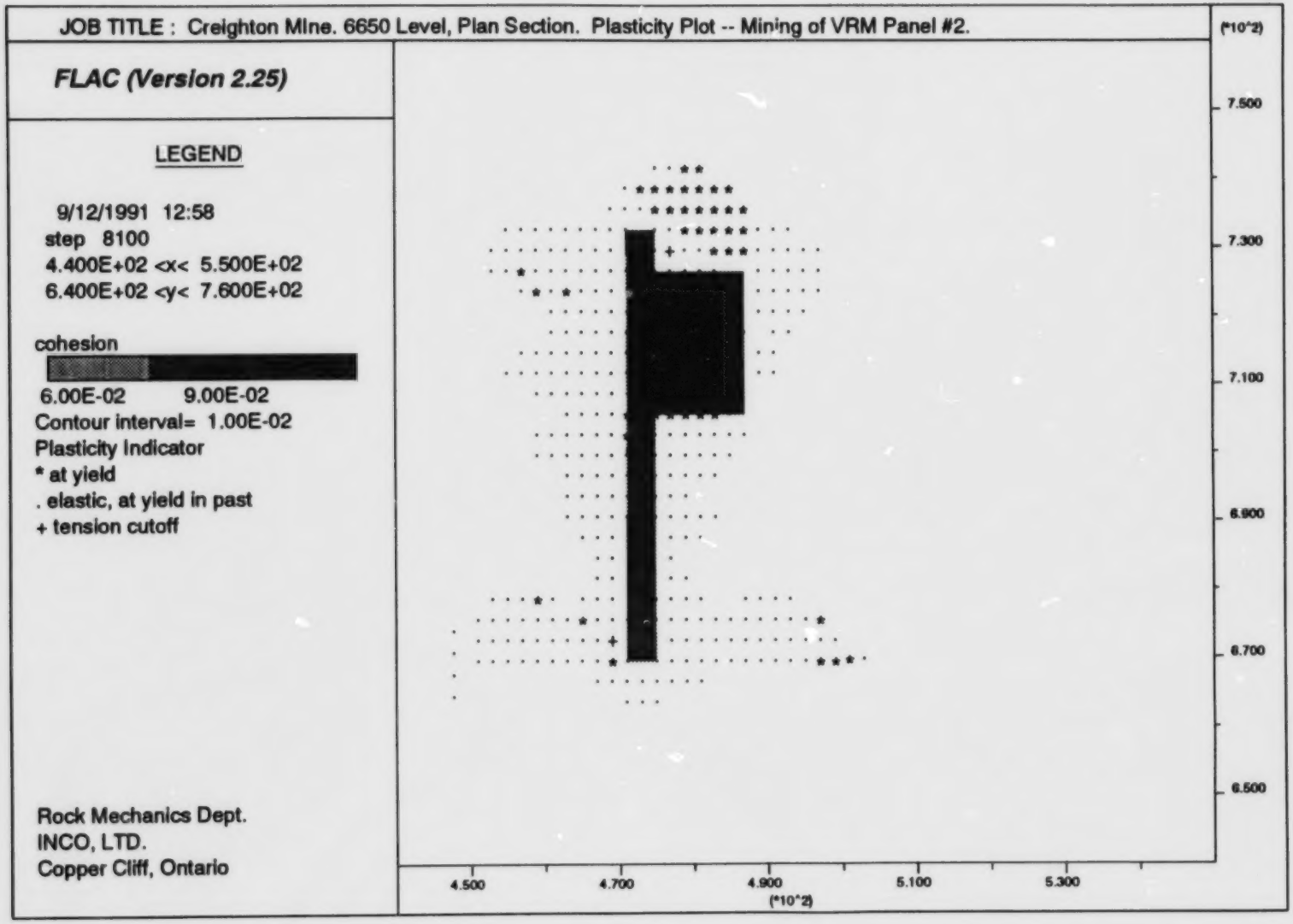

Figure 5-18 FLAC Model, Plan Section Mining of VRM Panel 2 -- Plasticity Plot

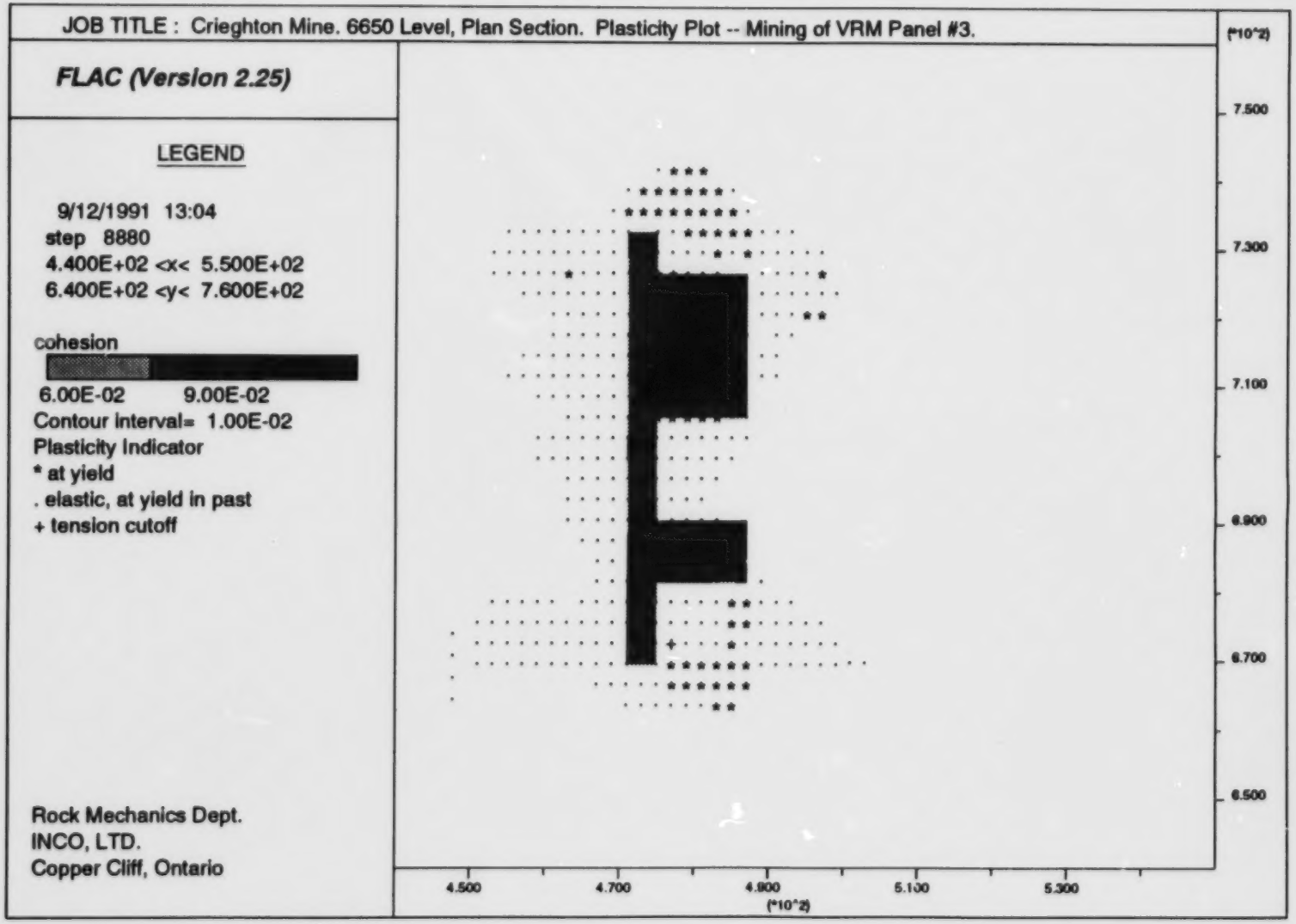

Figure 5-19 FLAC Model, Plan Section Mining of VRM Panel 3 -- Plasticity Plot

The mining of the last three VRM panels resulted in only a slight progression of the failure zone around the destress slot. These three panels are in the first row of the VRM mining, and directly next to the destress slot. The area of the rock mass immediately adjacent to the slot, has already failed due to the mining of both the slot and some of the VRM panels. The failure of the ground has been observed underground with the borehole monitoring equipment; the jointing in the rock appears loser, less-tight than the in-situ ground. When the ground fails, the load is shed to other areas of the rock mass; the stress contour plots indicate the areas which are highly stressed and also areas which are destressed.

The increase in plastic failure, which was observed underground, adequately correlates with the FLAC modelling results. The zone of plastic behaviour of the rock mass following the mining of the final VRM panels are represented in Figure 5-20 (mining of VRM panel #4), Figure 5-21 (mining of VRM panel #5) and Figure 5-22 (mining of VRM panel #6).

The stress magnitudes and distributions at the end of the mining sequence in the plan section model are depicted in Figure 5-23 (a), Sigma 1 Contour Plot, and Figure 5-23 (b), Sigma 2 Contour Plot.

These FLAC stress values were compared to an identical model using a purely elastic 2D program, BEM2D (refer to Figure 5-14). The stress results are almost identical; the minor difference can be attributed to the BEM2D model being purely elastic with only one material type while the FLAC model allows failure and contains three rock mass materials. The BEM2D stress results have been plotted. Figure 5-24 (a) represents the Sigma 1 Contour Plot and Figure 5-24 (b) is a plot of the Sigma 3 contours.

The FLAC stress values were also compared to the modelling results obtained from a 3D elastic numerical program, BEM3D. The comparison of the stress results from two modelling programs indicates that the stress magnitudes are within a 20% agreement. For a two-dimensional model, the FLAC stress results are considered to be within a reasonable amount of error at this point in the mining simulations. It was not deemed necessary to further calibrate the plan section model in an attempt to better match the stress values.

As a final calibration routine for the plan section modelling, the displacements predicted by the FLAC model were compared with the field instrumentation data.

The FLAC plan section modelling results predict a steady inward displacement of the slot walls; this inward x-displacement is more pronounced on the west side of the ore zone. The general direction of movement predicted by the FLAC model is in agreement with the field data. A FLAC Displacement Vector Plot, at the end of mining the destress slot and the 6 VRM panels, is shown in Figure 5-25.

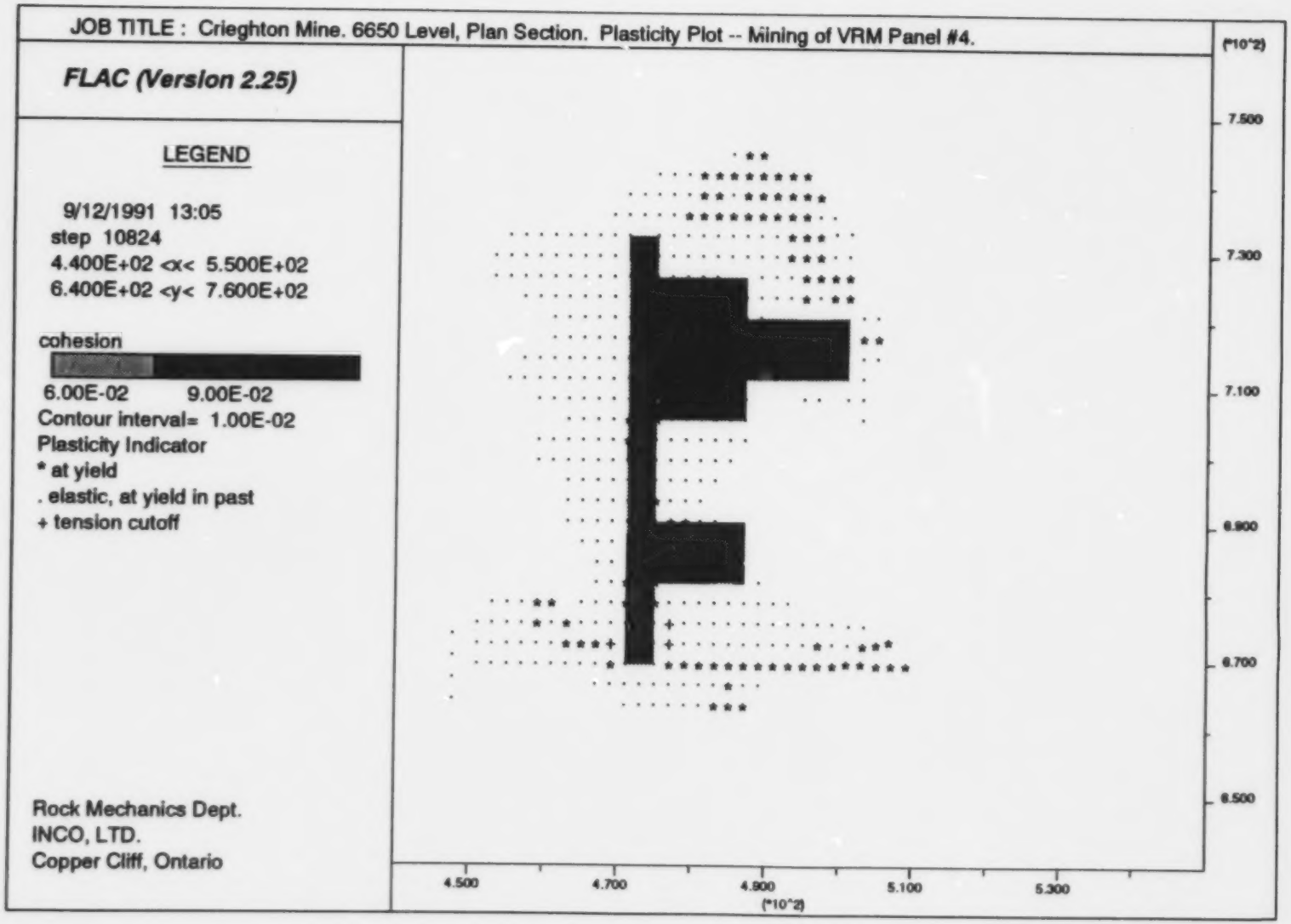

Figure 5-20 FLAC Model, Plan Section
Mining of VRM Panel 4 -- Plasticity Plot

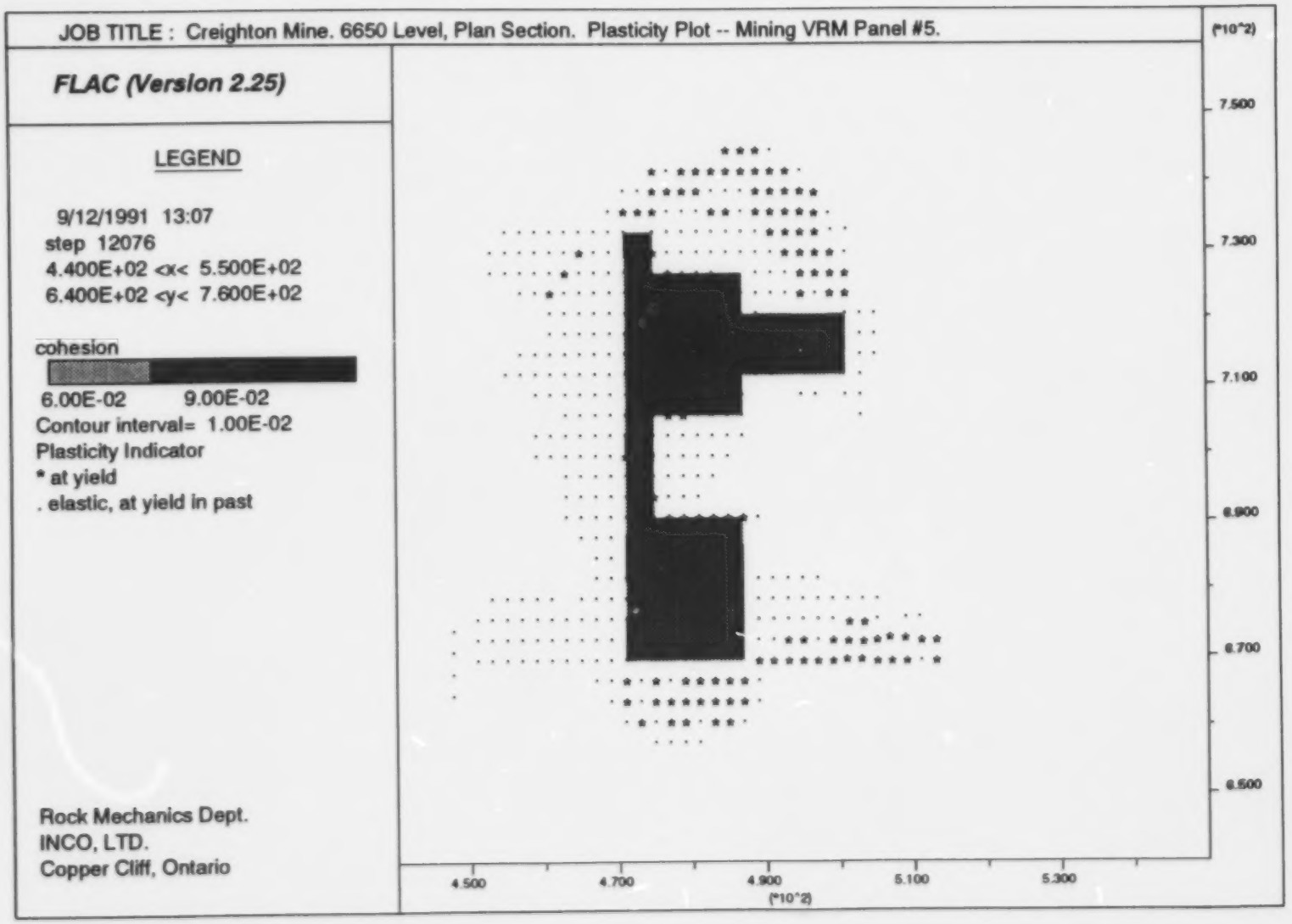

Figure 5-21 FLAC Model, Plan Section
Mining of VRM Panel 5 -- Plasticity Plot

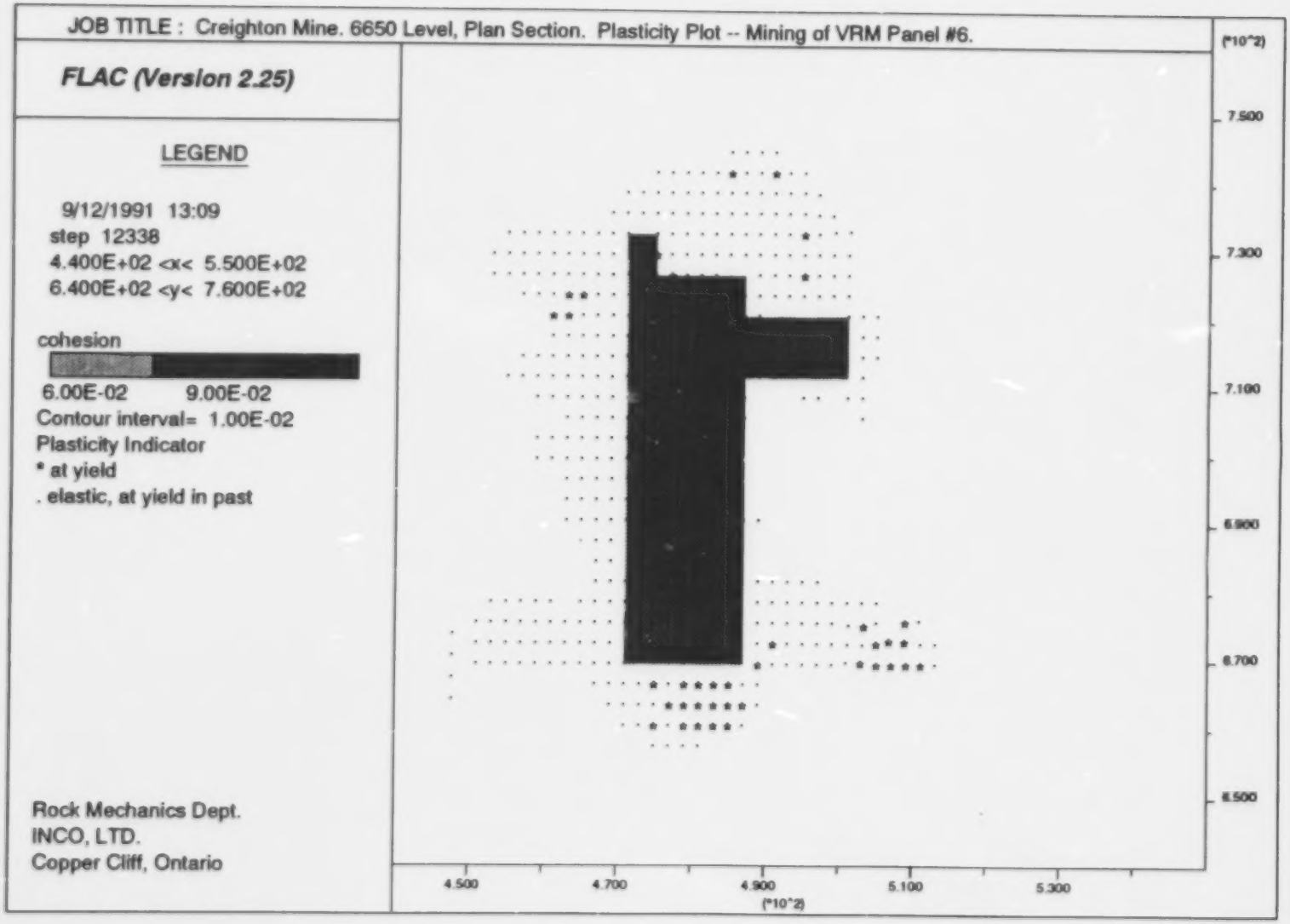

Figure 5-22 FLAC Model, Plan Section Mining of VRM Panel 6 -- Plasticity Plot

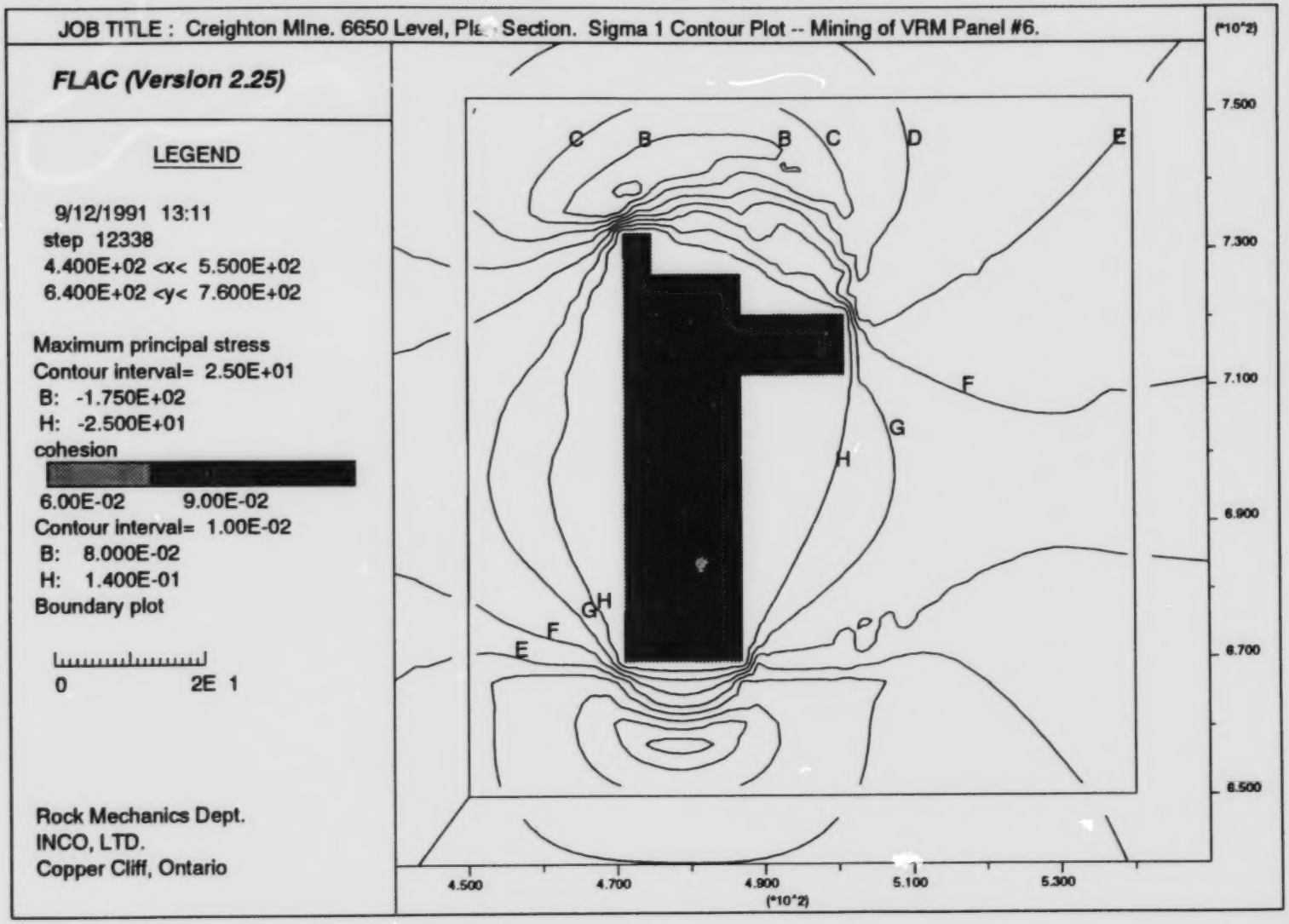

Figure 5-23(a) FLAC Model, Plan Section
Mining of VRM Panel 6 -- Sigma 1 Contour Plot

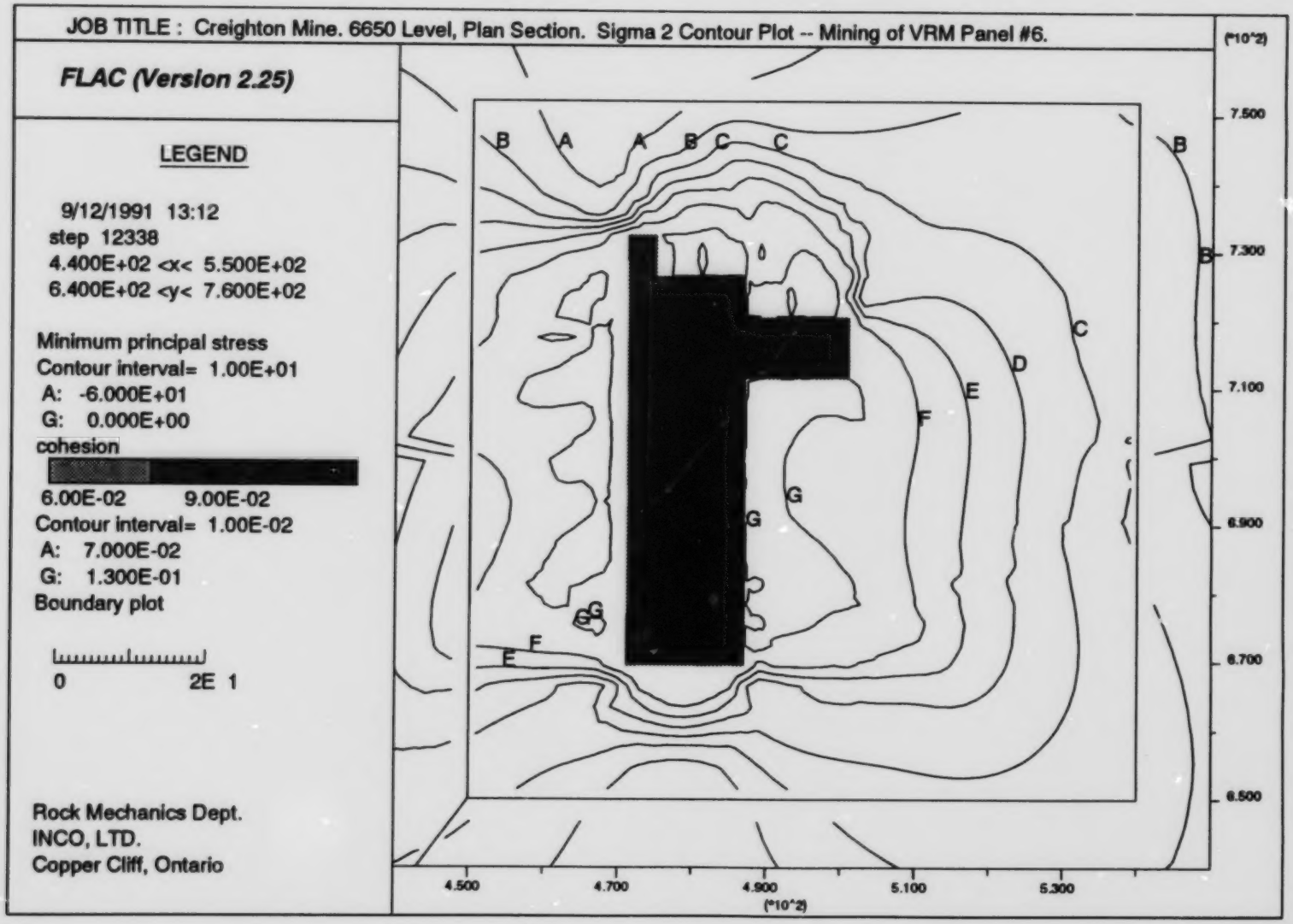

Figure 5-23(b) FLAC Model, Plan Section
Mining of VRM Panel 6 -- Sigma 2 Contour Plot

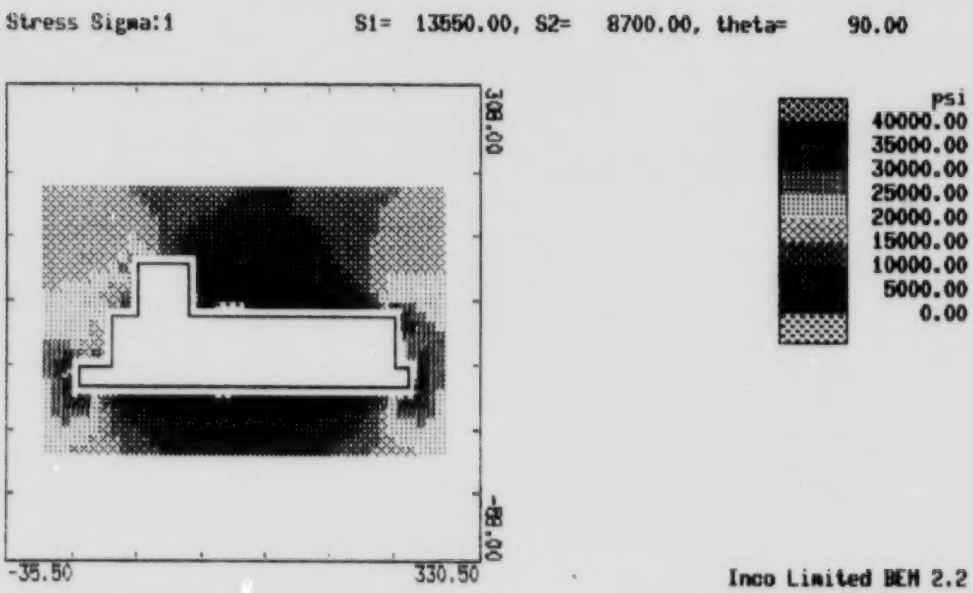

Figure 5-24(a) BEM2D Model, Plan Section
Mining of VRM Panel 6 -- Sigma 1 Contour Plot

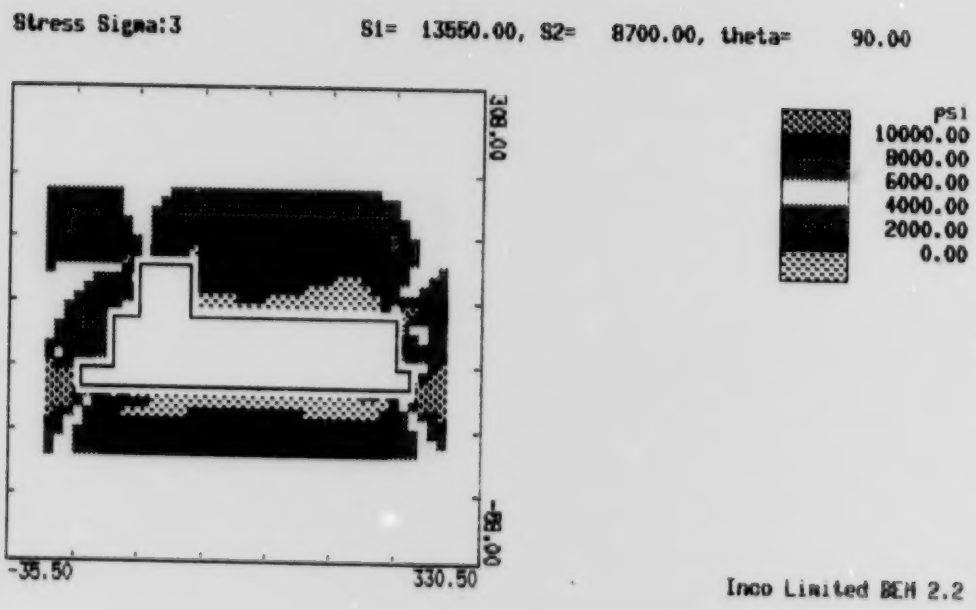

Figure 5-24(b) BEM2D Model, Plan Section
Mining of VRM Panel 6 -- Sigma 3 Contour Plot

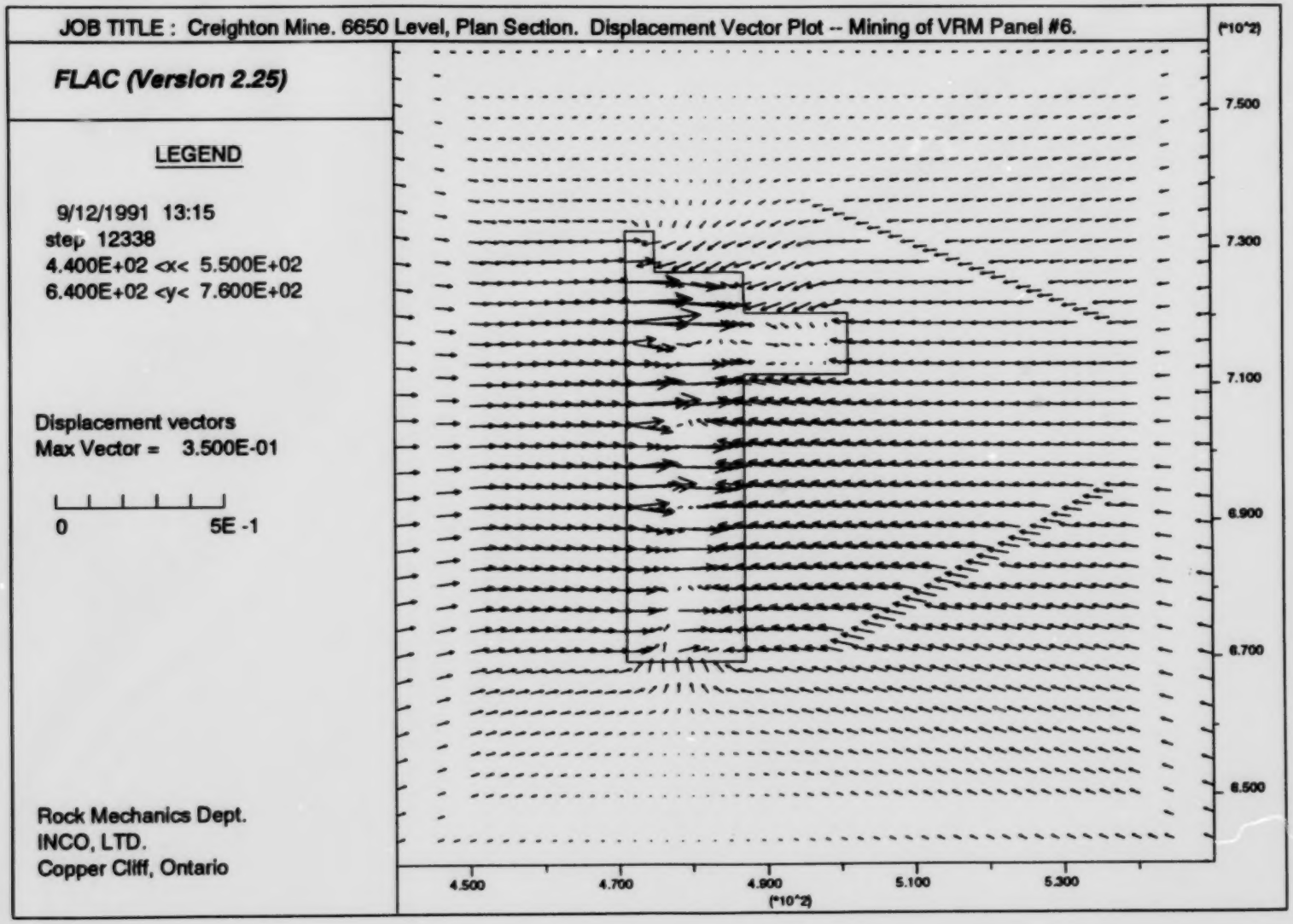

Figure 5-25 FLAC Model, Plan Section
Mining of VRM Panel 6 -- Displacement Vector Plot

The total inward displacement of the surrounding rock mass, at the end of mining the sixth VRM panel, was calculated using the FLAC model. The FLAC model predicted a total inward x-displacement of the rock mass of approximately 7 millimetres. The x-displacement is represented graphically with a history plot, Figure 5-26. This plot corresponds to a point within the rock mass on the eastern side of the slot, Figure 5-27.

This history point in the model is gradually moving inward with the progression of mining, until the final stage of mining, where the graph indicates that the total inward movement is 7 millimetres.

From the field monitoring information, the magnitude of x-displacement measured by the extensometers at the end of mining the sixth VRM panel was approximately 9 millimetres. The difference between the FLAC modelling and the actual field measurements is 2-millimetres in the x-direction.

Although the difference in x-displacements between the modelling and the field data is small, this variation corresponds to a 22% underestimation by the FLAC modelling. This amount of discrepancy, between modelling and underground instrumentation, is entirely reasonable considering the nature of the measurement. It is impossible to achieve closer accuracy with this form of measurement.

As stated earlier, the FLAC model, for this end-point in the mining simulation, is no longer behaving in plane-strain conditions. The effects of the upper and lower mining blocks cannot be taken into account with the model; this is another reason for the large discrepancy between the modelling results and the field instrumentation measurements.

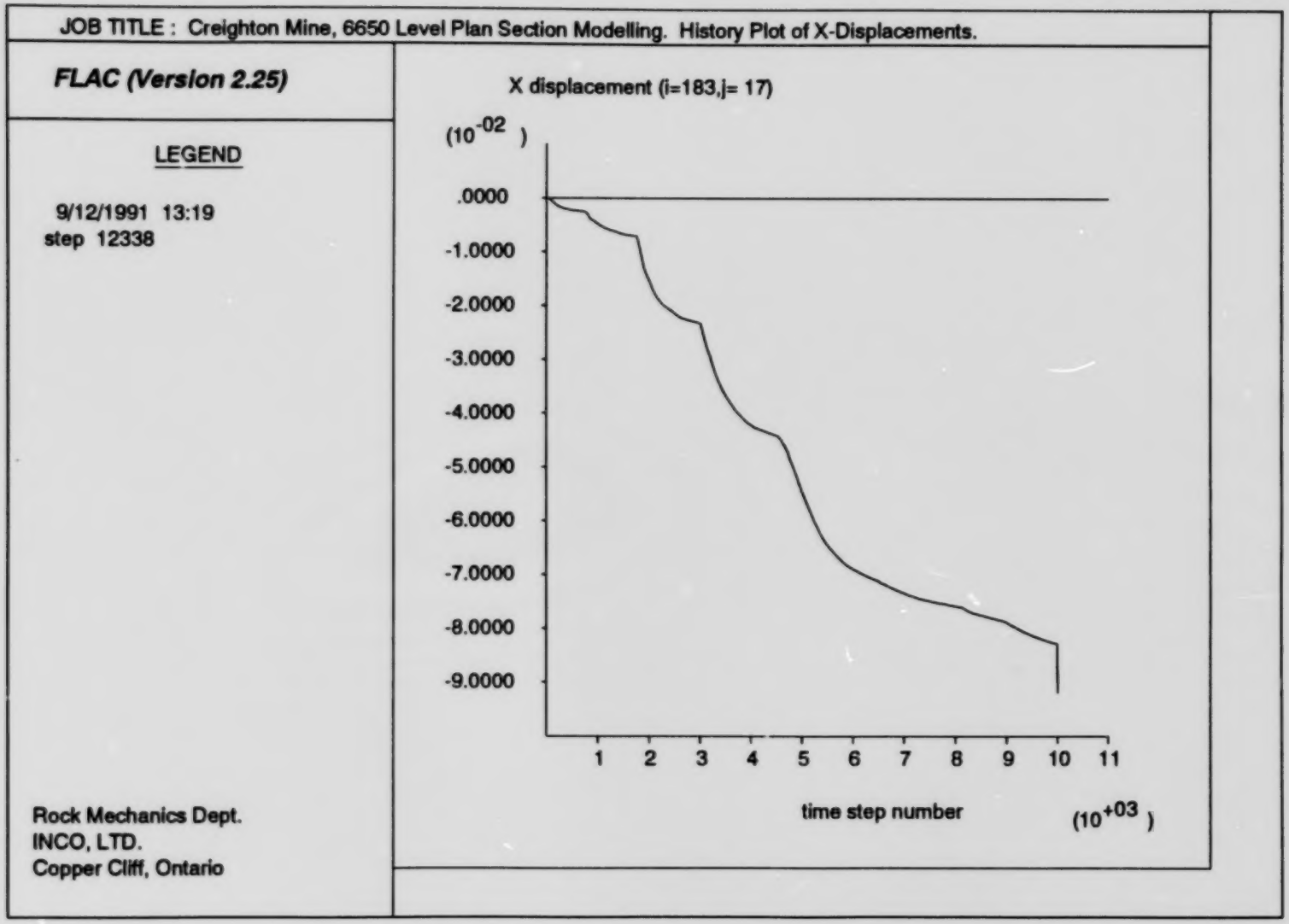

Figure 5-26 FLAC Model, Plan Section History Plot of the Total X-Displacement

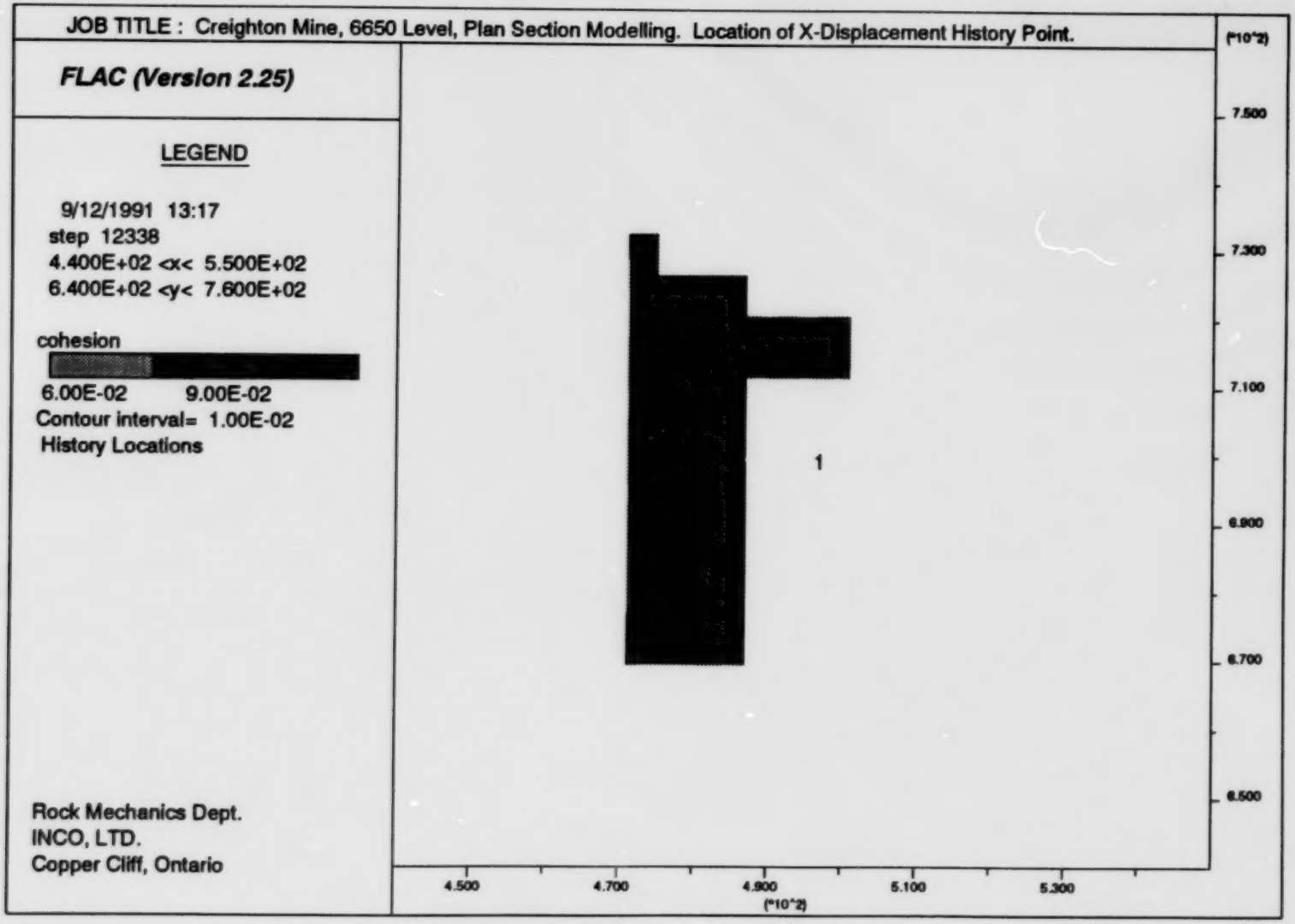

Figure 5-27 FLAC Model, Plan Section
Location of the X-Displacement History Point

5.4.2 Longitudinal Modelling Results

Unlike the plan section model, the longitudinal modelling geometry does not even remotely meet the required condition of plane-strain for 2D modelling. Despite this un-met condition, it was possible to set up the longitudinal model and successfully calibrate it against the field data and the BEM3D modelling stress results.

Because the upper mining area (6400-6600 Ore Block), the lower mining area (6700-6800 Ore Block), and the 4300 Ore Block were mined by mechanized cut-and-fill methods (with the use of transverse rib pillars as support), the representative longitudinal numerical model of the area is not straightforward.

Simulation of the rib pillar mining method using a two-dimensional numerical model is a difficult task to perform accurately. Firstly, the mining geometry, of the cut-and-fill stopes with the transverse pillars, is very complex. Even a coarse, 3D representation of the mining area is a difficult model to set-up accurately. Secondly, there is a lack of data for determining the strength parameters of the transverse rib pillars and hydraulic backfill. Only a general knowledge of the backfill and rib pillar performance in the mining areas was known; this information was used to calibrate the model.

In the first attempts at calibrating, the input parameters for the three rock types were set identical to the values used in the plan section model, refer to Table 5-12, page 5-28. However, the input parameters for the rib pillar and backfill combination were difficult to estimate. Although there was some instrumentation set-up for the measurement of fill stresses in the cut-and-fill areas, much of the data needed for the modelling was not available for the model calibrations.

Initially, the input parameters for the combination of the rib pillars and the backfill were set identical to straight 30:1 hydraulic backfill, refer to Table 5-13, page 5-29. These strength parameters were iteratively altered until the stress results within the FLAC model matched the stresses predicted from the previously calibrated BEM3D model. Once the initial model was calibrated, based on the stresses associated with the mining of the upper and lower ore blocks, some additional mining was simulated using the crown pillar failure for further calibrations.

The required strength parameters used to simulate the behaviour of the backfill and rib pillar combination are outlined in the following Table 5-15. These input parameters yielded stress results in the FLAC model which not only correlated to the BEM3D stress predictions but to the field data as well.

Backfill/Rib Pillar Combination-Resulting Input Parameters:

Elastic Properties:

$E = 11.0$ GPa
$\nu = 0.15$
Bulk Modulus = 5200 MPa
Shear Modulus = 4800 MPa
density = 2000 kg/m^3

Plastic Properties:

$\phi = 30°$
$C_o = 20$ MPa
cohesion = 5.8 MPa

Table 5-15 FLAC Input Properties for the Combined Effect of Hydraulic Backfill and Rib Pillars

The actual sequence of events which lead up to the failure of the crown pillar are described: -with the removal of the upper and lower ore blocks, the mining proceeded to the destress slot using the VRM method. At the same time, the 4300 Ore Block (above 6700 level, on the west end of the ore body) was being mined by mechanized cut-and-fill. As the mining in the 4300 Ore Block progressed upward from the 6700 level, the crown pillar thickness was gradually reduced until, at a vertical height of 90 feet, the crown pillar failed. The failure of the crown pillar is an assumption based on the occurrence of a large rock burst, which occurred in October 1987. This rock burst, together with the subsequent low-level seismicity and the lack of high stress related ground problems, indicate that the assumption of a failed crown pillar at 90-feet is reliable.

In order to model the failure of the crown pillar in a 2D long-section, the underground mining sequence could not be followed. In the model, the 4300 Ore Block was removed prior to both the destress slot mining and the VRM panel mining. This alteration in the mining sequence was necessary because, with the removal of the destress slot, the horizontal stress component would be completely cut-off in the 2D section. The complete loss of the horizontal stresses is not even a close approximation for the actual underground stress regime.

The horizontal stress component was maintained within the 2D model by delaying the slot mining until after the 4300 Ore Block mining. The model was fully calibrated when mining of the 4300 Ore Block, on the west side of the destress slot, caused the crown pillar to fail at the assumed 90-foot thickness.

The cut-and-fill mining method (using backfill and rib pillars) for the 4300 Block was simulated using the previously determined strength values for the fill, Table 5-15. However, this stiff fill material permitted a high degree of vertical stress transfer; this, in turn, prevented the failure of a 90-foot crown pillar. Even with unrealistic reductions in the ore zone strength, the crown would not fail.

In order to calibrate the model using the previously determined ore properties and the previously determined strength parameters of the backfill and rib pillars, the vertical stress transfer had to be reduced. Once the transfer of the vertical stresses was reduced by approximately 50%, the model could be calibrated. This value of 50% cannot be justified other than the fact that it is the only value that allowed the crown pillar to fail at the 90-foot thickness. The failure was also achieved with the input parameters for the rock mass (see Table 5-28) along with the previously determined strength parameters of the backfill and rib pillars.

The initial step for stress calibration involved a comparison between the BEM3D and the FLAC modelling results with just the extraction of the upper and lower mining blocks. The FLAC Sigma 1 Stress Contour Plot, at the completion of mining the upper and the lower ore blocks, is shown in Figure 5-28 (a). The Sigma 2 Stress Contour Plot for the same mining stage is shown in Figure 5-28 (b). The state of the rock mass has been plotted for the same stage in the mining sequence, Figure 5-29. It can be seen from this plasticity plot that the crown pillar is still intact; this is in further agreement with the assumed ground conditions at this stage in the mining sequence.

With the next mining step, the crown pillar was reduced to 120 feet in thickness; at this point the crown pillar was still mostly intact, as depicted with the FLAC state plot in Figure 5-30. When the crown was reduced to a thickness of 90 feet, the entire pillar was failed, Figure 5-31. The "state" plots indicate that the failure of the crown was progressive; it progressed upward from the westerly edge of 6700 level to the eastern edge of 6600 Level. The Sigma 1 Stress Contour Plot, for the 90-foot thick crown pillar is shown in Figure 5-32 (a). The Sigma 2 Stress Contour Plot is represented in Figure 5-32 (b).

Although the plane-strain conditions were not met, the longitudinal model was calibrated using the same rock mass input parameters as the plan section model. However, the confidence in the accuracy of these modelling results is lacking, especially due to the unreliable strength parameters for the rib pillars and backfill. As well, the predicted progressive mode of failure in the model does not correspond to the assumed sudden failure. The confidence in the results is even further reduced when one considers that the model could only be calibrated when the vertical stress transfer within the cut-and-fill stopes was significantly reduced.

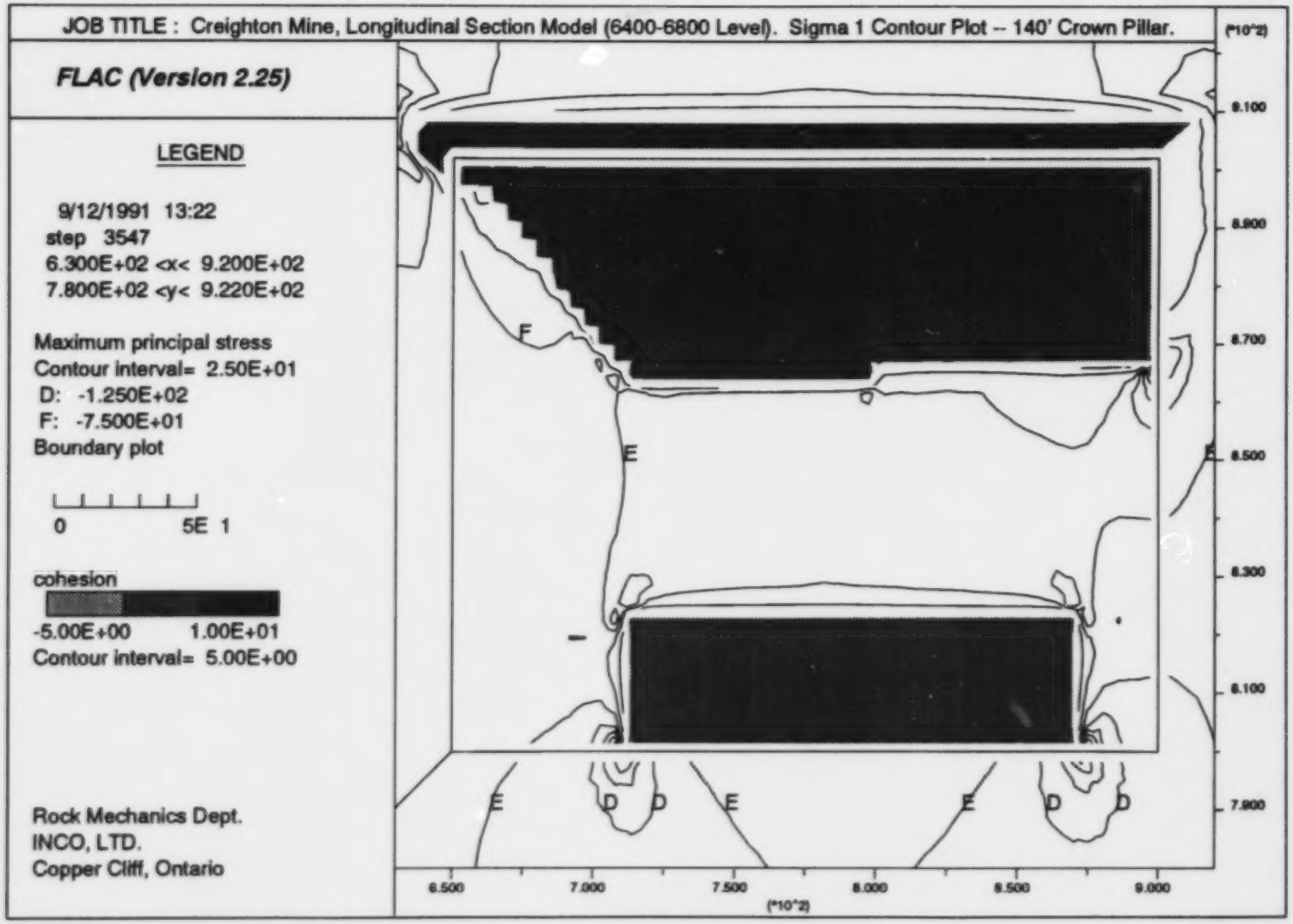

Figure 5-28(a) FLAC Model, Longitudinal Section Upper and Lower Blocks Mined. Sigma 1 Contour Plot.

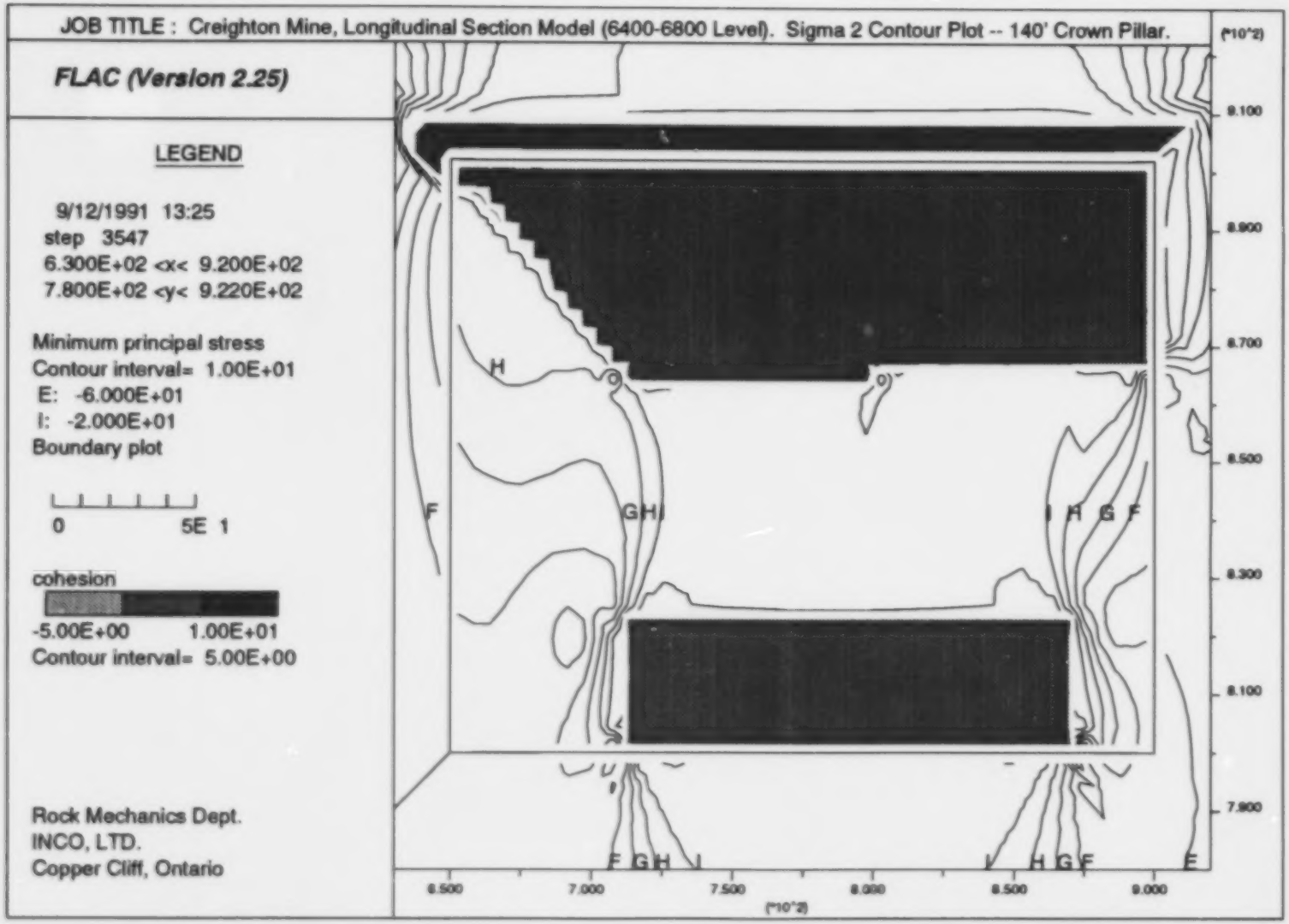

Figure 5-28(b) FLAC Model, Longitudinal Section Upper and Lower Blocks Mined. Sigma 2 Contour Plot.

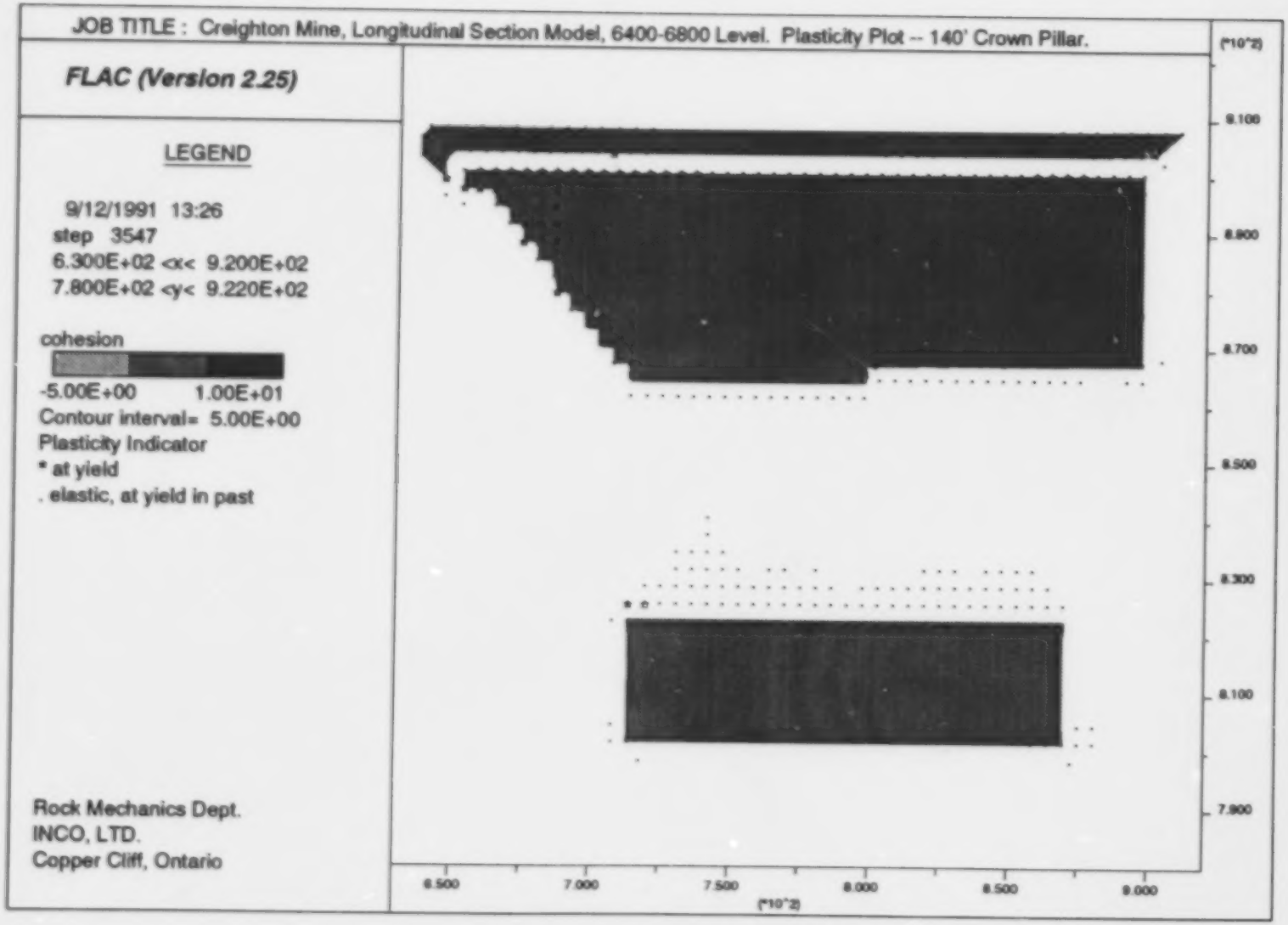

Figure 5-29 FLAC Model, Longitudinal Section Upper & Lower Blocks Mined (Crown=140') -- Plasticity Plot

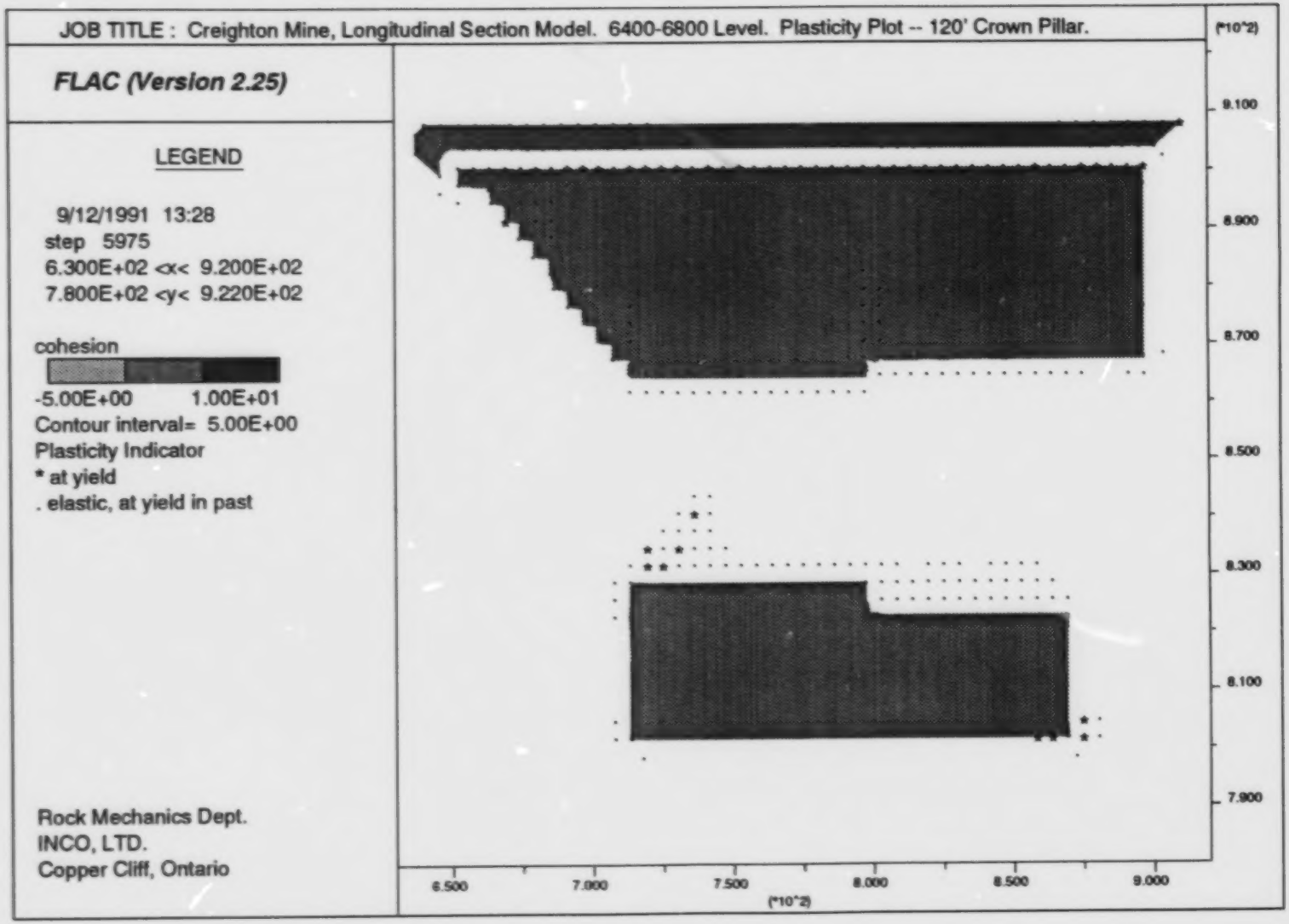

Figure 5-30 FLAC Model, Longitudinal Model
Crown Pillar Thickness of 120 Feet -- Plasticity Plot

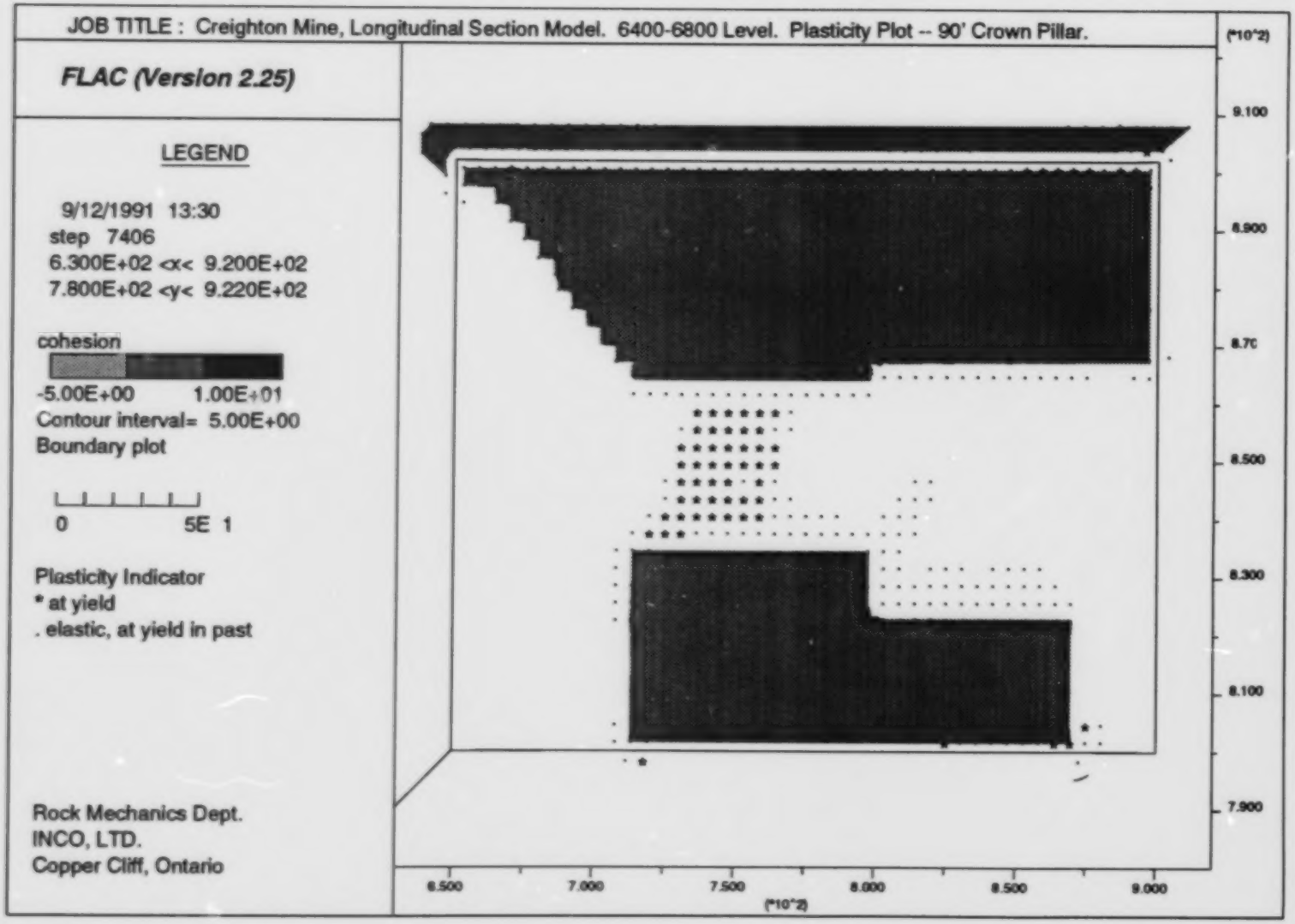

Figure 5-31 FLAC Model, Longitudinal Model Crown Pillar Thickness of 90 Feet -- Plasticity Plot

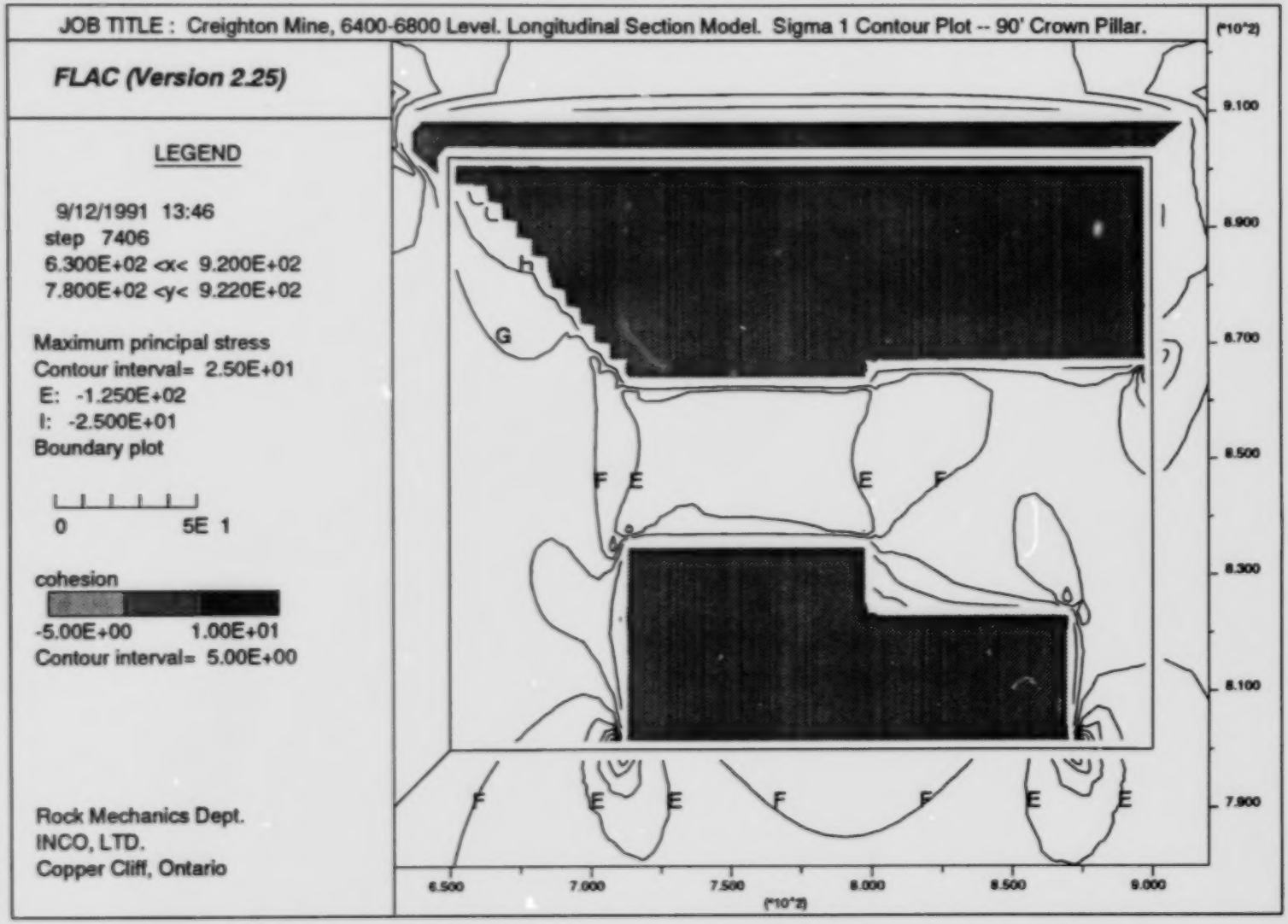

Figure 5-32(a) FLAC Model, Longitudinal Model
Crown Pillar Thickness of 90 Feet -- Sigma 1 Contour Plot

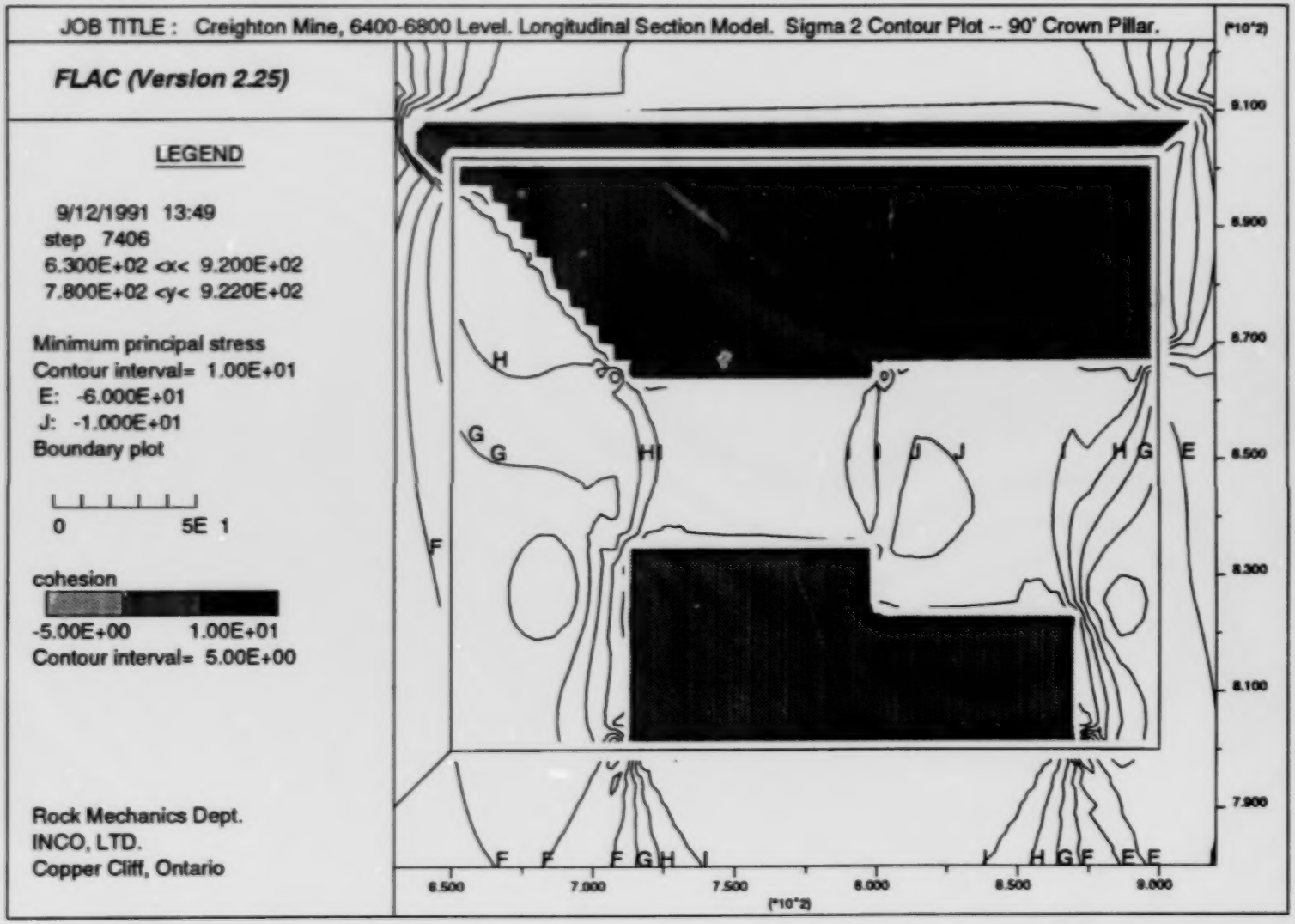

Figure 5-32(b) FLAC Model, Longitudinal Model Crown Pillar Thickness of 90 Feet -- Sigma 2 Contour Plot

5.4.3 Vertical Cross Section Modelling Results

Much like the longitudinal section model, the vertical cross-section modelling geometry does not meet the plane-strain condition which is required for 2D modelling. Nevertheless, it was possible to set up the model and calibrate it using the field site data and the BEM3D modelling stress results.

As with the two previous modelling calibrations, the results for the vertical section were compared and matched with the known ground behaviour of the case study site and the field measurements.

The sequence of events used for the calibration of this model are as described: following the mining of the first VRM panel and some mining within the 4300 Ore Block, a large rockburst occurred below the 6600 level. This rockburst occurred in October 1987, at the end of mining a VRM panel; it is assumed that the failure of the crown pillar coincided with the occurrence of the rockburst. The crown pillar, at this time, had been excavated up to a vertical height of 27 metres (90 feet). This 90-foot crown pilar thickness was used in calibrating the model and for the purpose of model calibration, the failure of the crown is considered valid.

As with the longitudinal model, the cross-section model could not be set-up using the exact underground mining sequence. The simulation of the destress slot mining and the VRM panel mining is not possible within the model; the mining of the slot and the VRM panels would completely cut-off of the horizontal stress component in the 2D section. In order to obtain a close representation of the 3D stress regime, the destress slot mining and the VRM panel mining were not simulated within the 2D model. Only the mining on the western section of the ore zone, in the 4300 Ore Block, was simulated for model calibration. This model is more representative of the actual three-dimensional stress regime, and allows for a reasonable calibration of the crown pillar failure.

Because the actual area above 6700 level, in the 4300 ore block, was mined using mechanised cut-and-fill methods with transverse rib pillars as support, the same rib pillar and backfill combination input parameters that were used in the longitudinal section modelling were used in the cross-section modelling. These strength values are summarized in Table 5-15, page 5-64. The input parameters used for the three rock types were also identical to the two previous modelling scenarios, Table 5-12, page 5-28.

With the extraction of the upper ore block and the easterm section of the lower ore block, the FLAC stress results were in agreement with the BEM3D modelling results for the same stage in the mining. However, when the simulation of additional mining in the lower ore block (and in the 4300 ore block) was commenced, the crown pillar would not fail. Even when the ore strength parameters were reduced to unrealistically low values, the crown would not fail.

The resistance to crown pillar failure was attributed to the stiff fill (representing the rib pillars and backfill) within the upper and lower mining blocks; the fill was permitting a high degree of vertical stress transfer. The vertical stress transfer through the upper and lower mining blocks was gradually reduced until, at a reduction of approximately 50%, the crown pillar was able to fail at a thickness of 90-feet.

The FLAC "state" plot of the 140-foot crown pillar, after mining the upper and lower ore blocks, is shown in Figure 5-33. This plasticity plot indicates that the crown pillar is primarily intact with only some minor failure in the vicinity of the two large openings. This prediction of the rock mass state agrees with the ground conditions for this stage in the mining. The FLAC "state" plots for successive mining within the 4300 ore block demonstrate the mode of failure of the crown pillar: Figure 5-34 (130-foot crown pillar), Figure 5-35 (120-foot crown pillar), Figure 5-36 (110-foot crown pillar), and Figure 5-37 (100-foot crown pillar). These plots indicate that the crown pillar failed progressively. At a vertical thickness of 27 metres (90 feet) the crown was entirely failed; this is depicted in the FLAC "state" plot in Figure 5-38. The failure, as determined from the modelling, originated at the footwall corner at the 6700 level and progressed upward in a shearing mode to the hangingwall contact at the 6600 level.

The predicted stress regime for the 140-foot crown pillar is shown in Figures 5-39 (a), for sigma 1 contour plot, and Figure 5-39 (b), for sigma 2 contour plot. Also, the stress contour plots for a 90-foot crown pillar are represented in Figure 5-40 (a), sigma 1, and Figure 5-40 (b), for sigma 2. These stress plots agree, within reason, to the BEM3D stress results.

The results of the vertical section calibration modelling indicate some contradictions regarding the mode of crown pillar failure. The model indicated progressive failure, which is in agreement with the results of the longitudinal model, but neither of the models are in agreement with the assumed ground behaviour. From the documentation of the rock mass behaviour, the crown failure was assumed to be sudden, with the occurrence of the October 1987 rockburst. Despite the lack of agreement for the mode of failure, the calibration of the vertical section model was successful.

Note that the strength parameters for the backfill and rib pillar combination were identical to the values used in the long-section model. Likewise, both models required that the vertical stress transfer through the rib pillar/backfill material be reduced by approximately 50%. This manipulation of the input data is not surprising considering the almost total lack of plane-strain conditions within both of the models. Despite achieving model calibration, not much confidence can be placed on the accuracy of the modelling results.

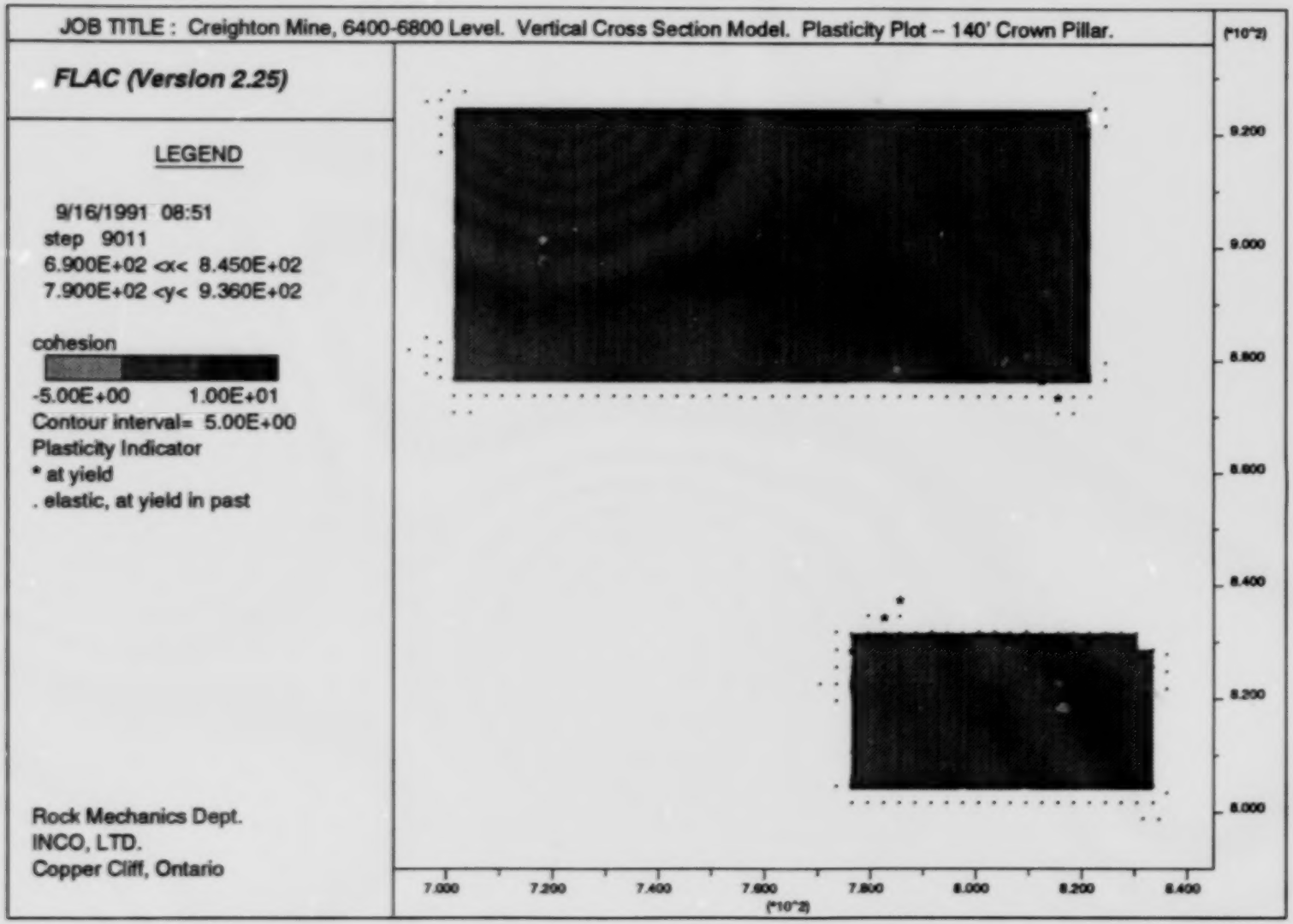

Figure 5-33 FLAC Model, Vertical Section 140-Foot Crown Pillar -- Plasticity Plot

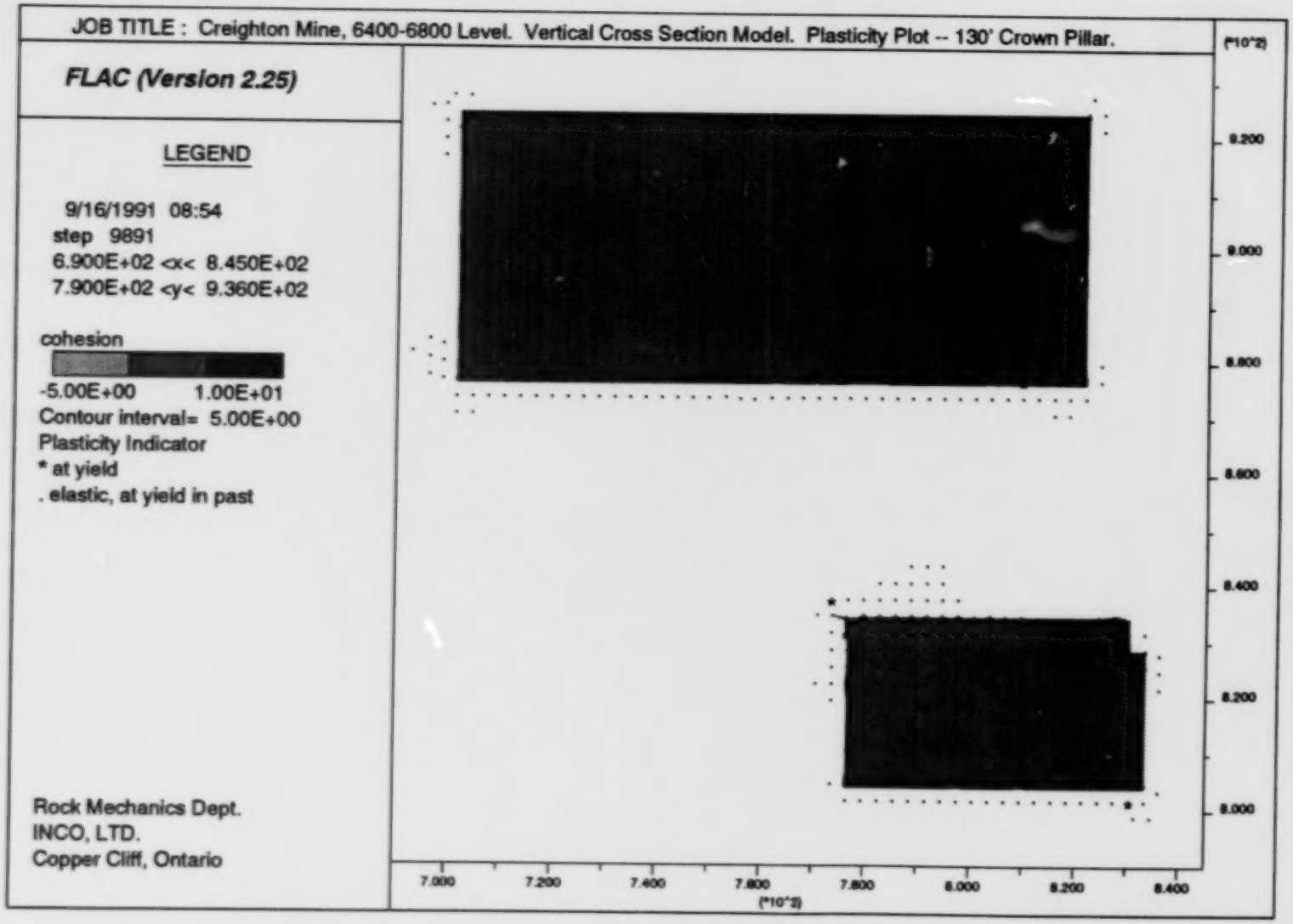

Figure 5-34 FLAC Model, Vertical Section 130-Foot Crown Pillar -- Plasticity Plot

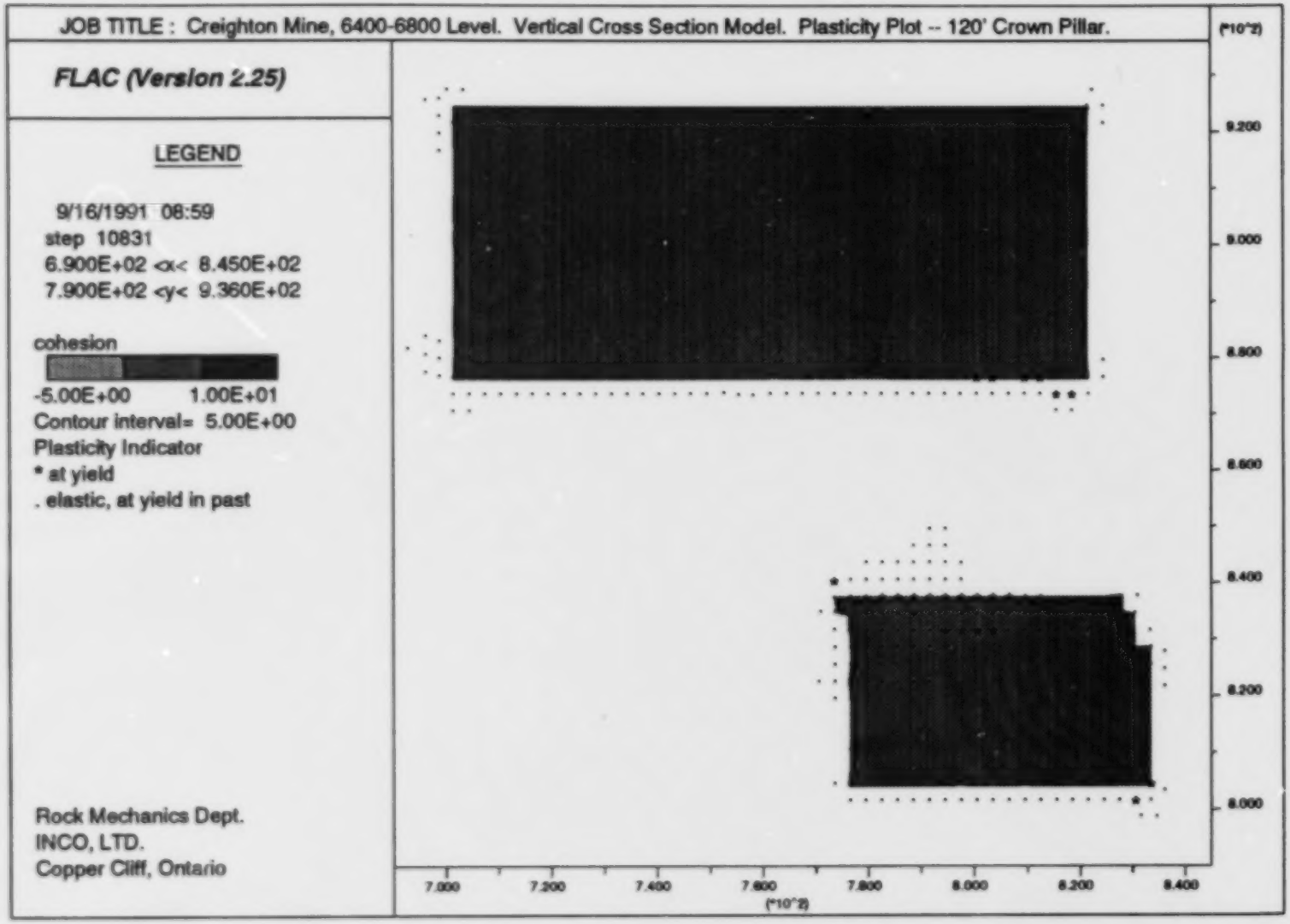

Figure 5-35 FLAC Model, Vertical Section 120-Foot Crown Pillar -- Plasticity Plot

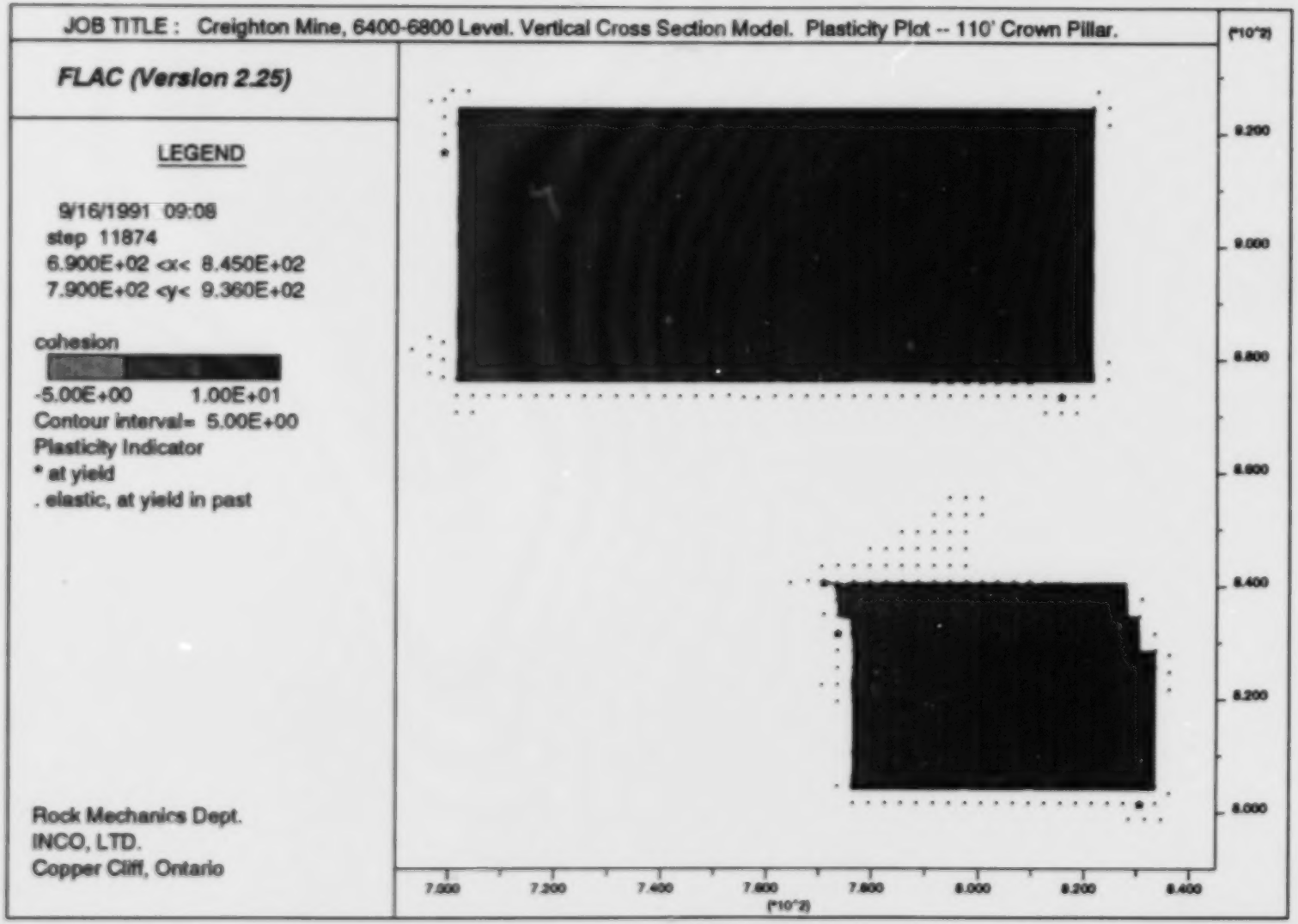

Figure 5-36 FLAC Model, Vertical Section 110-Foot Crown Pillar -- Plasticity Plot

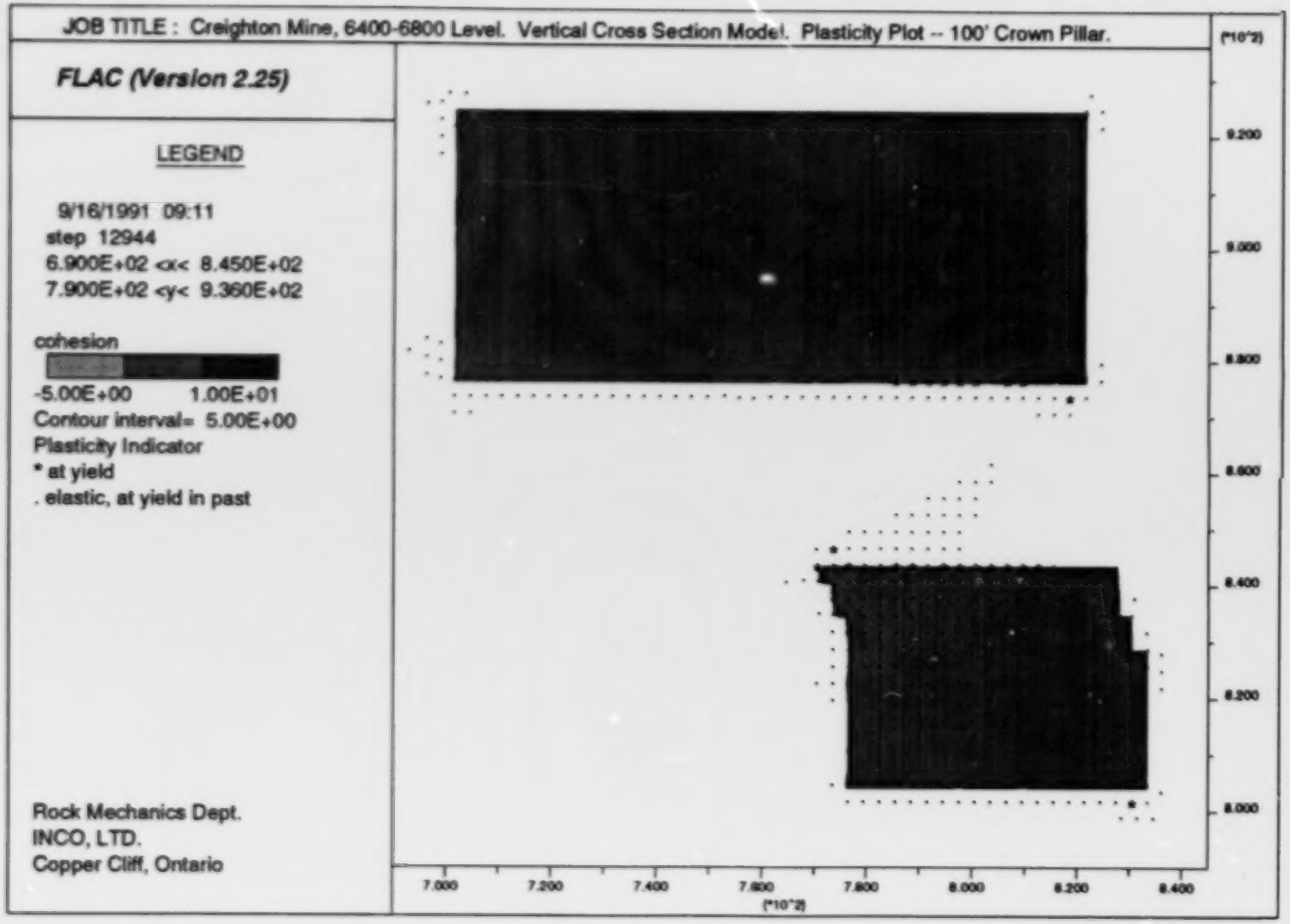

Figure 5-37 FLAC Model, Vertical Section
100-Foot Crown Pillar -- Plasticity Plot

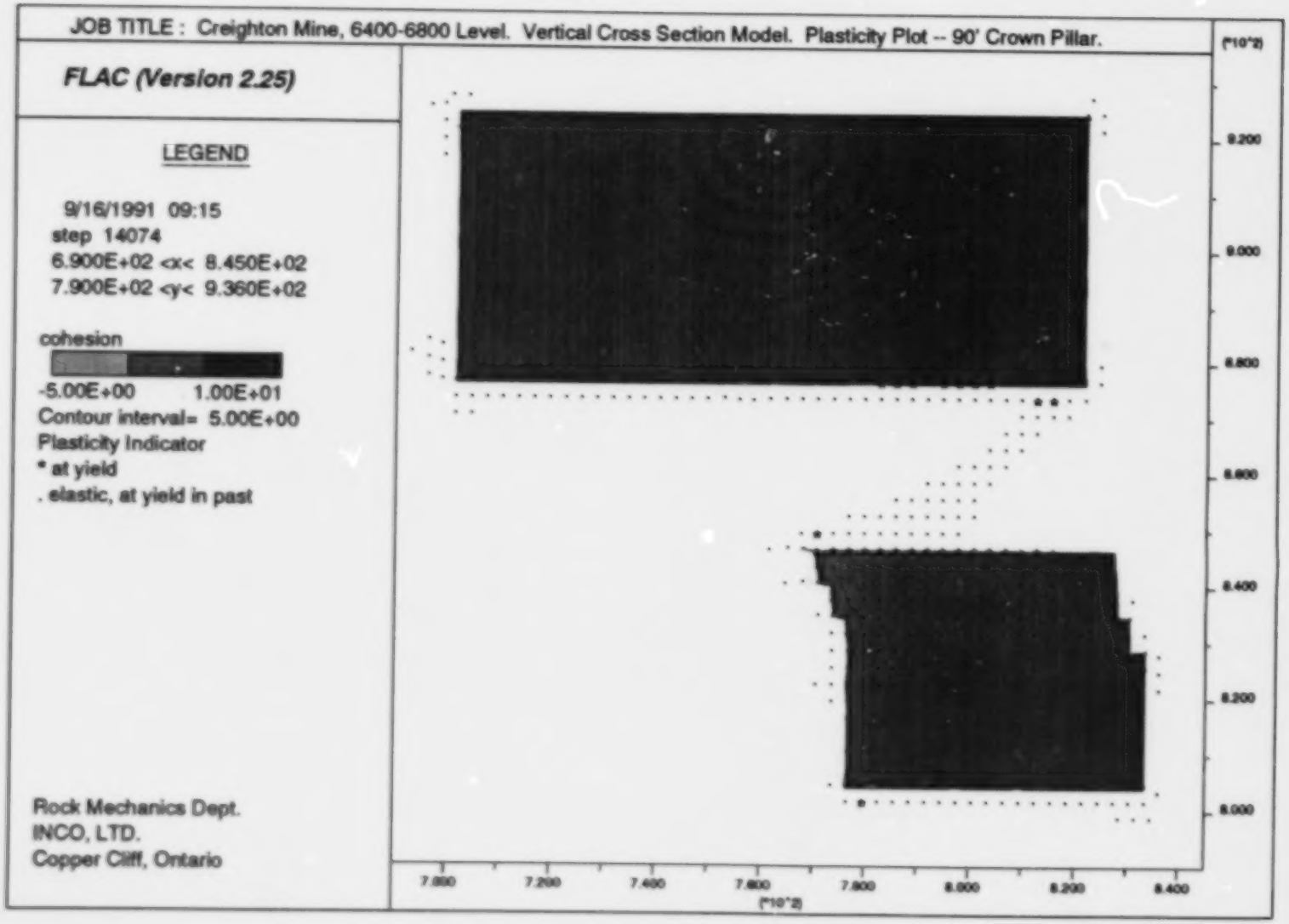

Figure 5-38 FLAC Model, Vertical Section 90-Foot Crown Pillar -- Plasticity Plot

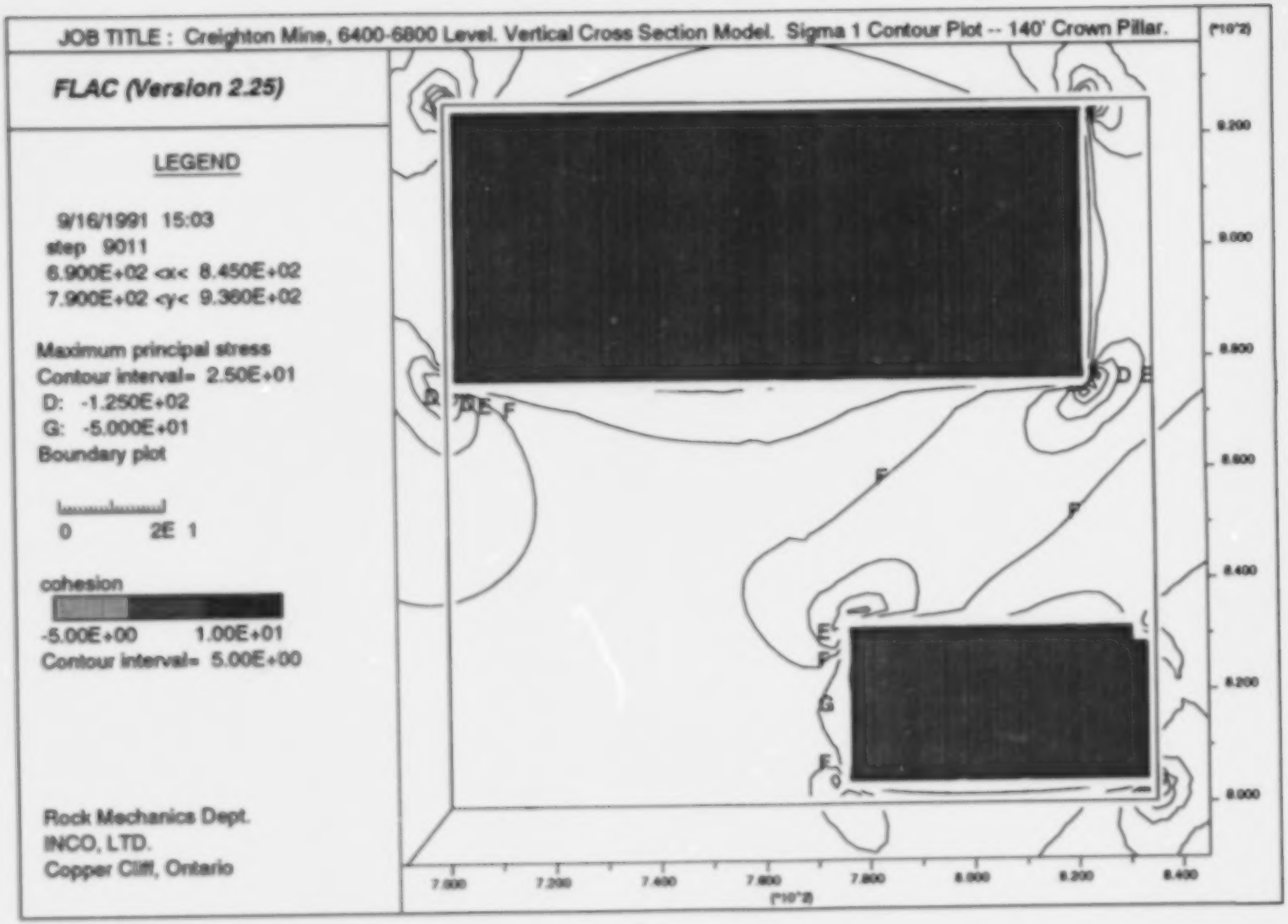

Figure 5-39(a) FLAC Model, Vertical Section
140-Foot Crown Pillar -- Sigma 1 Contour Plot

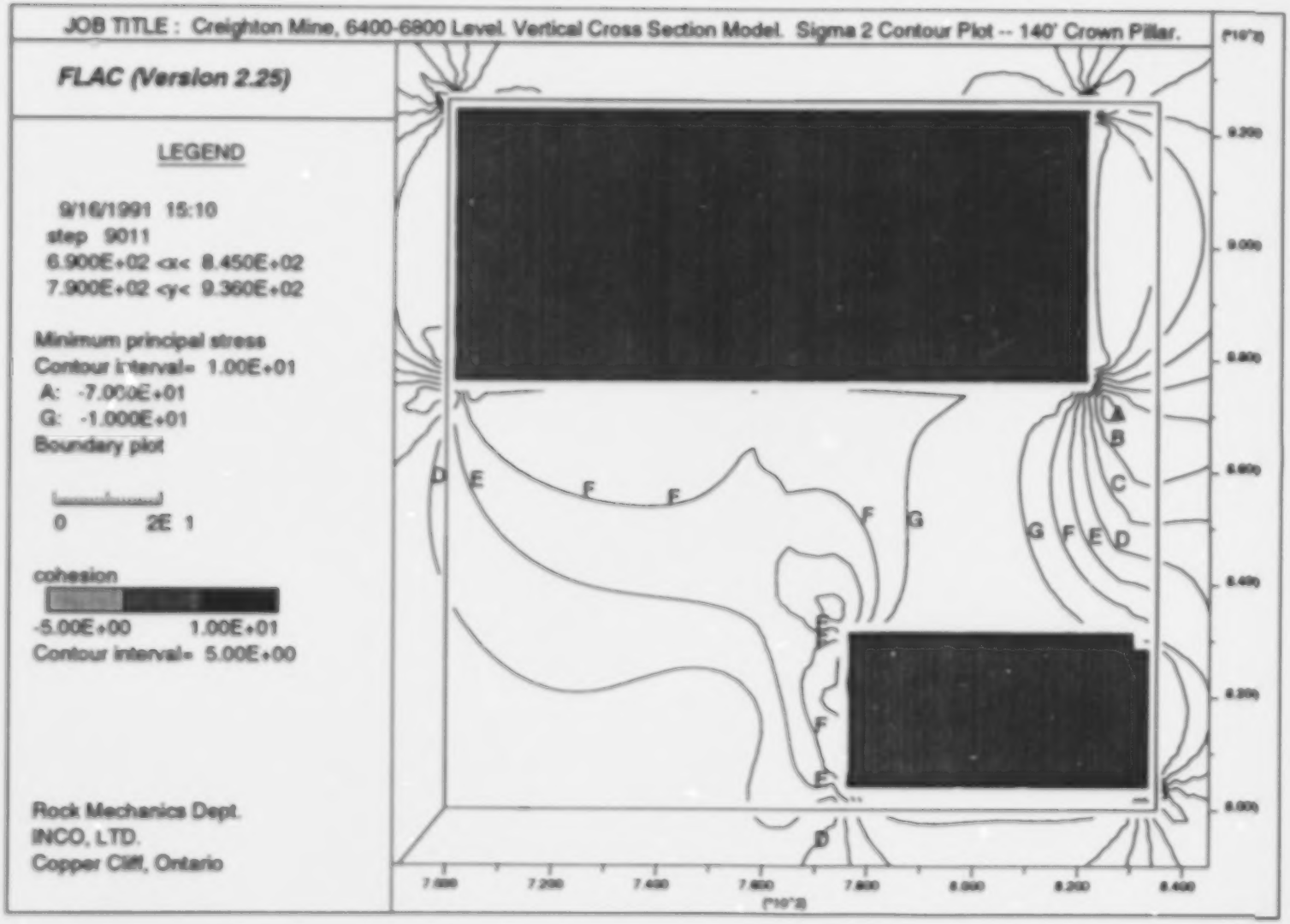

Figure 5-36(b) FLAC Model, Vertical Section 140-Foot Crown Pillar -- Sigma 2 Contour Plot

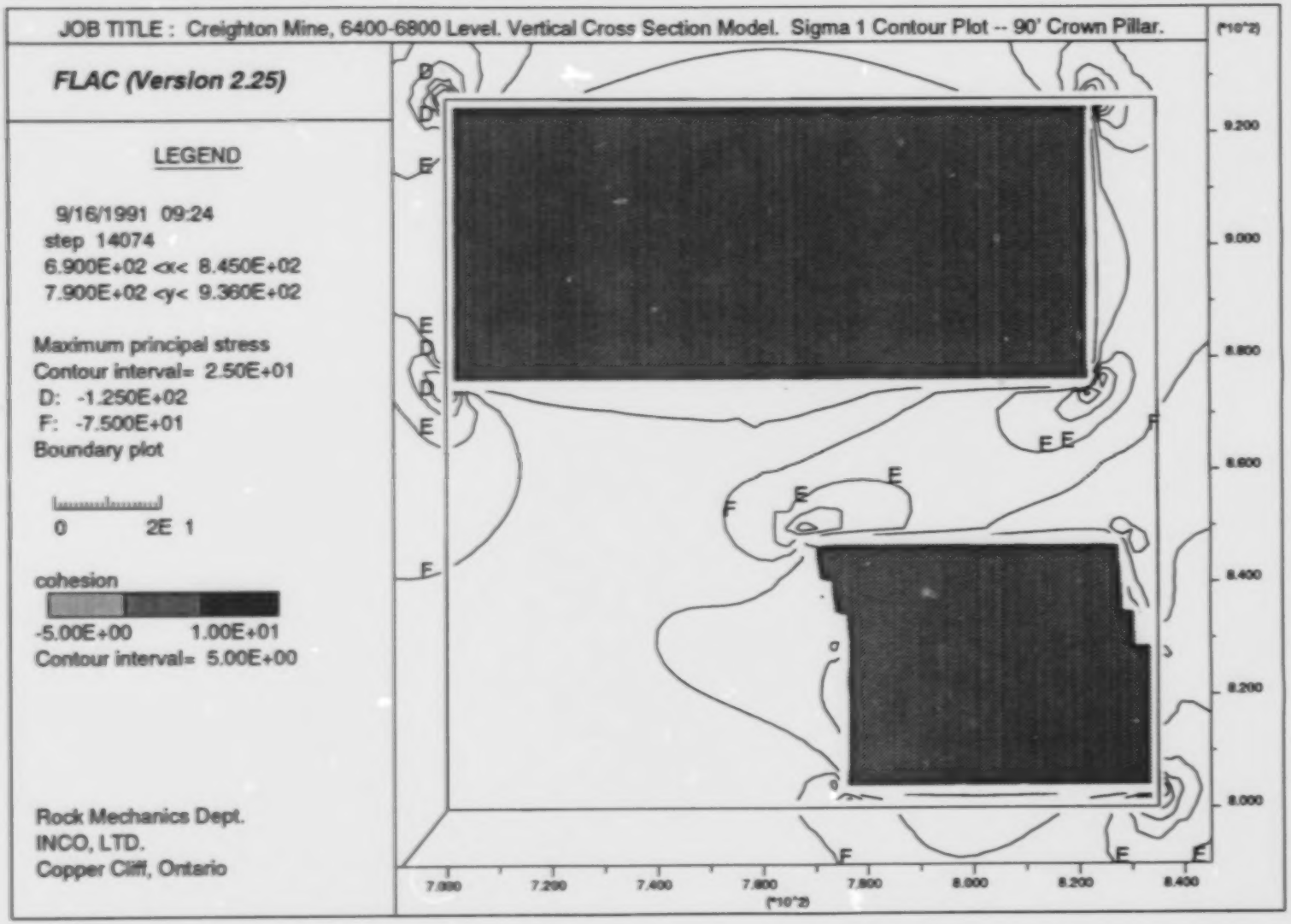

Figure 5-40(a) FLAC Model, Vertical Section
90-Foot Crown Pillar -- Sigma 1 Contour Plot

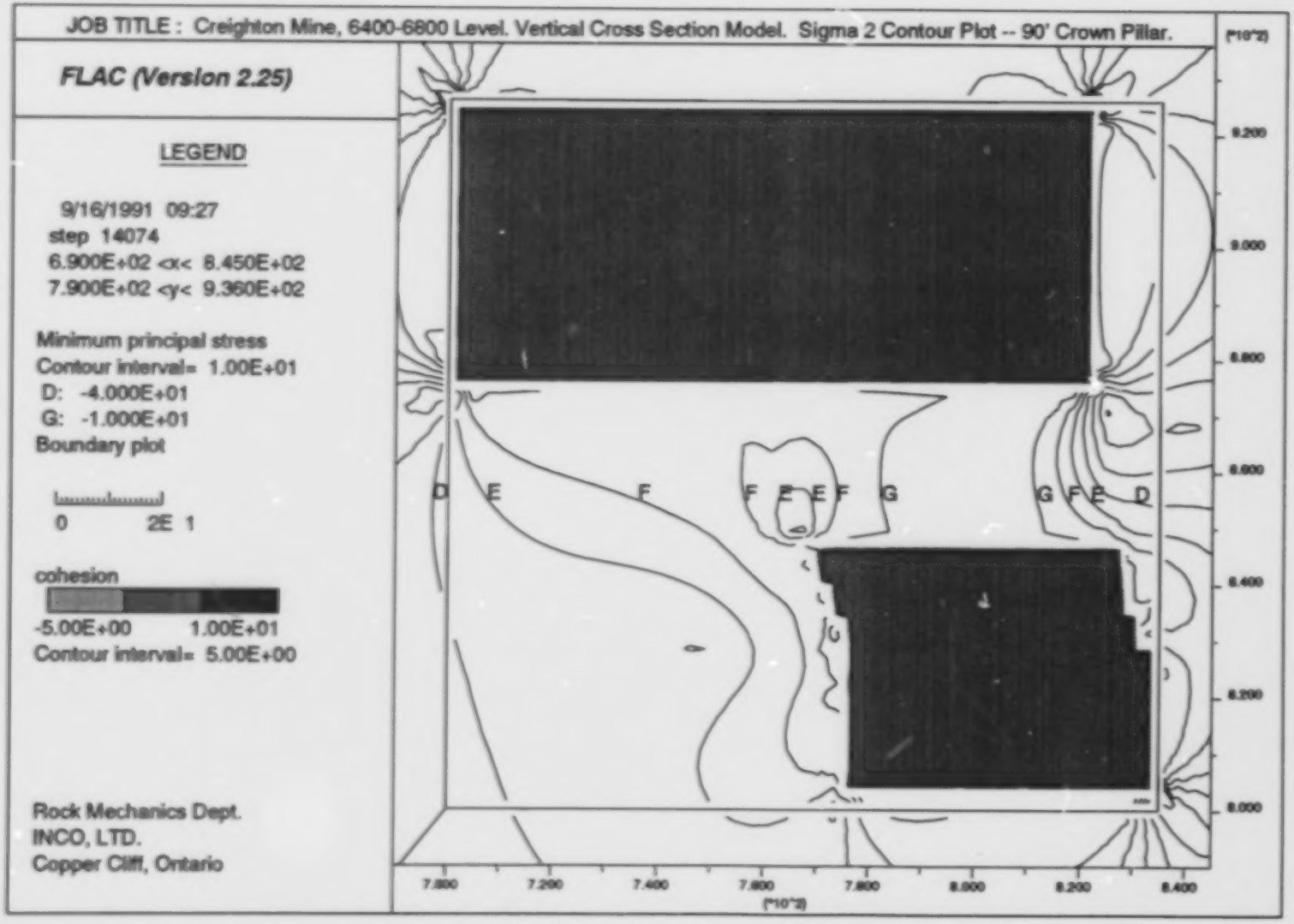

Figure 5-40(b) FLAC Model, Vertical Section
90-Foot Crown Pillar -- Sigma 2 Contour Plot

5.5 Comparison of the Modelling Results with the Field Results

The three 2D modelling geometries of the case study site were successfully calibrated with the field data and the known ground conditions. The input parameters for the rock mass properties for the three section models were identical; the resulting set of input properties are outlined in Section 5.4. This agreement of input properties for the three different models may be a coincidence, or the parameters may be a true representation of the case study site.

All of the geometries did not exhibit the plane-strain conditions which are required for two-dimensional modelling. As well, the effect of all of the other mining areas at Creighton Mine could not be established within any of the section models prior to simulating the mining in the case study site itself. The previous mining would have had an obvious effect on the stresses, displacements, and the predicted failure zone within the 6600-6700 crown pillar; however, it is impossible to determine the amount of inaccuracy that is represented within the modelling sections.

The modelling results indicate that there are some significant discrepancies with the instrumentation data. In particular, the displacements predicted by the FLAC models differ up to 30% from the measured displacements (extensometers and inclinometers). As well, the stress magnitudes are within a 20% agreement with the BEM3D modelling and with the underground stress measurement data.

The results of the vertical section and the longitudinal section calibration modelling indicate some contradictions regarding the mode of crown pillar failure. Both of the models indicate gradual failure of the crown pillar which originated at the footwall contact on 6700 level and progressed upward in a shearing mode to the hangingwall contact on 6600 level. The actual failure of the crown pillar is assumed to be sudden, with the occurrence of a large rockburst in October 1987. Despite the lack of agreement for the mode of failure, the thickness of crown pillar failure (at 90-feet) was successfully calibration within the vertical section and longitudinal section models. It was necessary, however, to reduce the vertical stress transfer through the backfill material within the upper ore block (6400-6600 level) and the lower ore block (6700-6800 level) by 50% before the calibration of the 90-foot crown pillar failure could be accomplished.

Obviously, the plan section model cannot be calibrated for the failure of the crown pillar, however, the model was calibrated using the borehole camera data and some stress monitoring information. The extent of the relaxed ground, determined from the borehole camera, was matched to the predicted area of failure from the FLAC plan section model. Despite calibration with the extent of relaxed ground, the effects of the upper and lower mining could not be incorporated within this plan model, and therefore, some inaccuracies with the modelling results are presumed.

6.0 2D PLASTICITY MODELLING

The numerical modelling code, MINE2D, is a research program which was developed as part of a COMDA contract. It is the precursor to the development of a 3D plastic, boundary element code called MINE3D. The MINE2D program was developed in-house at Inco, Mines Research, in Sudbury. This is a two-dimensional program which utilizes the boundary element formulation. There is the capability within the code to model fault/slip features, multi-materials, and the elasto-visco-plastic behaviour of the modelling medium. For further details on the MINE2D modelling development and usage, refer to Volume 2 and Volume 5.

The MINE2D numerical modelling program was used in the calibration process of the Creighton Mine 6600-6700 Ore Block Study. One modelling geometry was used to simulate the mining in the vicinity of the 6600-6700 ore block. This is a vertical cross-section taken through the ore body from the 6400 level and extending down to the 6800 level; this geometry is identical to the vertical section used in the FLAC numerical modelling. The vertical section represents the western portion of the mining zone where the ore body is the widest, from the hangingwall to the footwall. Although this section does not fully adhere to the necessary plane strain conditions, it is the only section which most-closely represents a plane strain case.

In the initial calibration process, the MINE2D numerical modelling results were directly compared to both the field data and the FLAC modelling results. The comparisons involved an iterative process whereby the MINE2D input parameters were progressively altered until the modelling results closely correlated to the FLAC modelling results. The MINE2D results were also compared to the known ground behaviour of the case study site. The net result of the calibration is a model which agrees with all of the known data.

The main purposes for carrying out this sequence of calibration modelling with the MINE2D program are defined below:

1) MINE2D was used to model the case study area using the plasticity capabilities. When the results of the model match the field data, the final set of input parameters are to be used as the initial input for the verification modelling of the case study site with the MINE3D program.

2) The MINE2D results were to be compared to the results of the FLAC modelling using identical input parameters. The discrepancies between the models were to be noted.

3) Since MINE2D is the predecessor to the MINE3D code, any discrepancies between identical FLAC and MINE2D modelling would be useful for proving or disproving the MINE3D code.

6.1 MINE2D

MINE2D is a two-dimensional numerical modelling program which has been developed in-house at INCO, Mines Research. This program was intended to be a research tool for the further development of a 3D plasticity code based on the same boundary element formulation.

The MINE2D program has the ability to simulate the elasto-visco-plastic behaviour of the modelled medium. As well, the program has the capability of modelling the effects of multi-materials and fault/slip features. In relation to the case study area, the calculation capacity for the multi-materials and plasticity have been utilized.

6.1.1 Plasticity Parameters

In order to set up a model using MINE2D, there are a list of essential requirements to be fulfilled. Refer to Volume 5, MINE2D USER'S MANUAL for a complete description of the modelling requirements and the set up of the input data files. In general, the required input parameters for a MINE2D model depend on the type of geomechanics study that is to be performed. In order to determine a zone of failure in a rock mass, a plasticity model must be initialized using either the Mohr-Coulomb or the Hoek-Brown Failure Criterion. In order to remain consistent with the 2D plasticity modelling, a Mohr-Coulomb plasticity model was set up with the MINE2D code. The required input parameters are listed in Table 6-1.

Rock Properties: Basic Elastic Properties: E - Young's Modulus ν - Poisson's Ratio Additional Properties for Plasticity Modelling: ϕ - Internal Angle of Friction C_o - Uniaxial Compressive Strength T_o - Tensile Strength Stress Values: Sig1 - horizontal stress component Sig2 - vertical stress component Note: these stresses can be oriented in any direction.

Table 6-1 Input Requirements for a MINE2D Plasticity Model

6.1.2 Post-Processing

In terms of general output, the MINE2D code can display a wide variety of results. With respect to the calibration models, the results that are of interest are: the stress levels, the stress distributions, the displacements, and the extent of the plastic failure zone.

In terms of hardcopy results, the stress levels, the displacements, the strains, and the zone of plastic failure (or the "state" of the rock mass) are represented with filled contour plots for ease of interpretation.

6.2 Calibration Methodology

The MINE2D code has the capability of simulating the elasto-visco-plastic behaviour of a rock mass. Because of this capability, the MINE2D program was used to model the 6600-6700 ore block in order to calibrate the model against known field data.

The general calibration procedure for the case study model was through an iterative series of model runs and successive alterations to the input parameters. The model was considered to be fully calibrated when the input parameters produced modelling results which directly correlated to the instrumentation data and the known ground behaviour.

The actual process used in the calibration was by direct comparison with the FLAC numerical modelling results. This direct comparison was used since the FLAC model of the case study area was previously calibrated using the field data and known ground behaviour. The eventual outcome from the fully calibrated MINE2D model (and the FLAC model) is a set of input parameters which will be used as initial input for the verification modelling of the case study site using the MINE3D program.

The MINE2D modelling of the case study site was directly compared to the FLAC modelling for a second reason. The FLAC numerical model is a "proven" 2D plasticity code while MINE2D is not. Any discrepancies between identical FLAC and MINE2D models can be used in either proving or disproving the legitimacy of the MINE2D code.

There is a third reason for conducting a direct comparison of the MINE2D results with the FLAC results. Both the MINE2D and MINE3D programs are based on the same calculation scheme; both codes use a boundary element formulation with the inclusion of plasticity calculations. Any proving or disproving of the MINE2D code, through the comparison of the results with the FLAC modelling, will be further reflected on the eventual verification of the MINE3D code.

Additional to the comparisons to FLAC, the MINE2D models were compared to a series of identical BEM2D models to ensure the MINE2D code was providing reasonable results. Note that the two stress components used in BEM2D are σ_1 and σ_3; the corresponding stress components in MINE2D are σ_1 and σ_2.

6.2.1 Stress Relaxation Zone Estimation

As with the FLAC program, the MINE2D code can indicate the areas within the rock mass which are behaving in an plastic manner. The user may see the areas of plastic behaviour by plotting the Failure Zones. The image displays the zones which are either currently yielding or have previously yielded.

For further information on the plastic behaviour, the Strains can be plotted. This information yields the zones within the model which have undergone some form of displacement. The areas which have high strains are usually indicative of areas where more damage has occurred. The sign convention used in MINE2D is as follows: positive strains indicate compression while negative values correlate to tension.

The methodology for determining the stress relaxation zone with the FLAC code is similar to the estimation methodology used in the MINE2D program. Zones within the model which have stresses exceeding the strength of the rock mass have progressed from elastic behaviour into the plastic portion of the curve; these zones are plotted.

6.3 Model Preparation

In order to set up the MINE2D calibration model of the 6600-6700 ore block, there are some input parameters to quantify: (i) the model geometry, (ii) the stress state, and (iii) the input properties. Basically, the MINE2D calibration model was set up identical to the calibrated vertical-section FLAC model.

6.3.1 Model Geometry

One numerical modelling geometry was used for the MINE2D calibration process. This simplified two-dimensional section, taken through the instrumented area, was chosen in order to achieve a representative model of the ore zone to the west of the destress slot. The model geometry is identical to the FLAC vertical cross-sectional model. Although this is a simplified geometry it has been configured for a fast and reliable analysis without jeopardizing the overall results. The MINE2D model is a vertical cross-section taken mid-strike along the ore body, Figure 6-1.

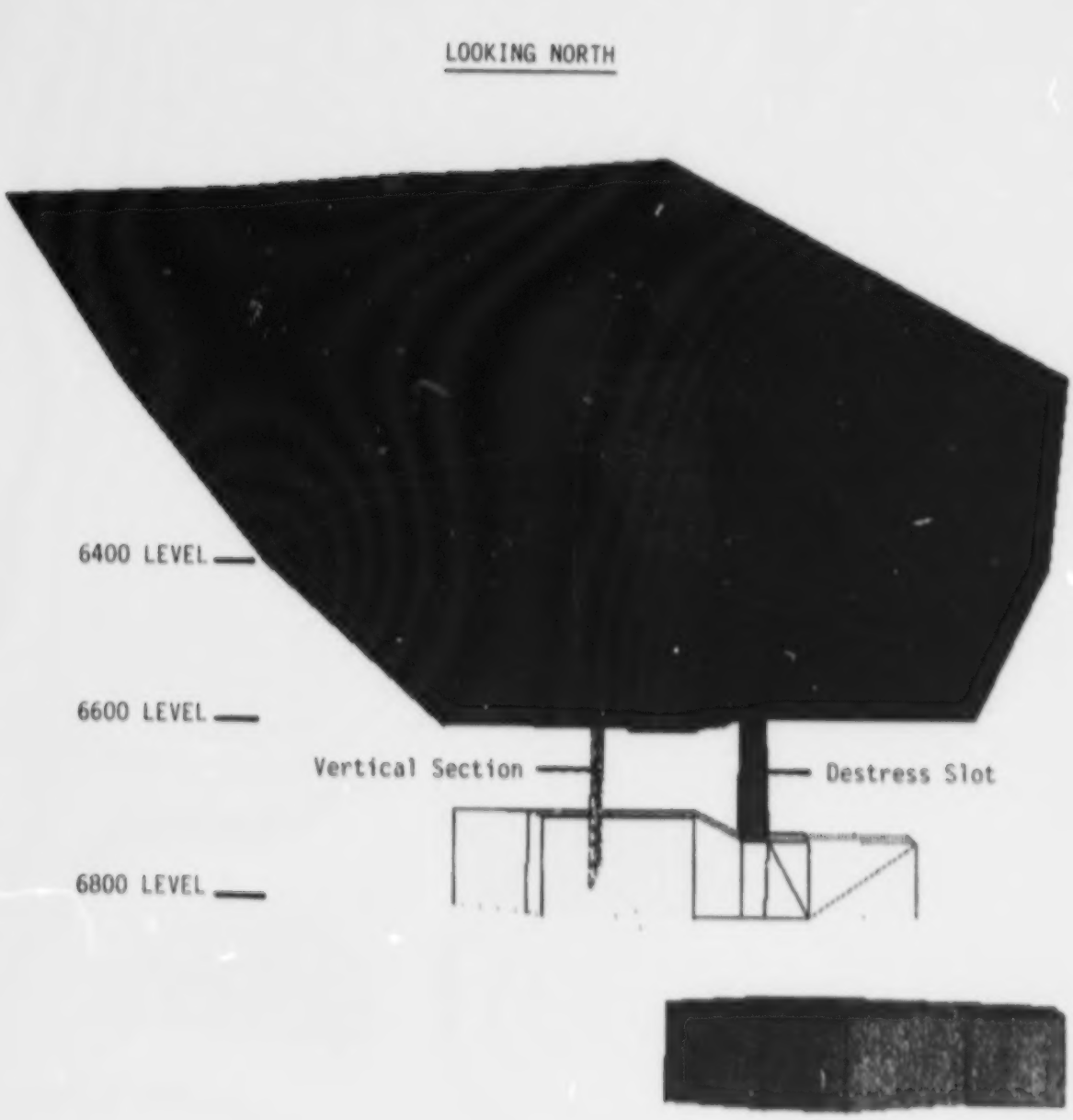

Figure 6-1 Location of the Vertical Cross-Section Used in the MINE2D Modelling

Although the actual mining geometry of this section is far from being a true-representation of the plane strain conditions required for 2D modelling, this is the closest approximation of plane strain modelling anywhere within the 6600-6700 Ore Block.

The validity, or lack thereof, for using 2D modelling to simulate a 3D problem is not known until the model has been run and the results have been analyzed. A simple analysis of the calibrated MINE2D model, by comparing the input parameters for MINE2D with the previously determined input parameters for FLAC, will determine this validity of using the 2D modelling codes. Ideally, the input values should be the same for the FLAC and the MINE2D models since they each represent the identical mining geometry, input parameters, and mining history.

6.3.2 Geology

Within the 6600-6700 ore block, there is only a subtle variation in the geology. The ore zone is primarily composed of massive sulphides, however there is a transgression into disseminated sulphide ore toward the hangingwall rocks. The hangingwall is largely composed of norites while the footwall is made up of granites with some inclusions of gabbroic rocks. The geologic lithologies have been divided into three distinct zones for simplification in the MINE2D modelling. The three main zones are as follows:

1) massive sulphides -- ore zone
2) granites -- footwall
3) norites -- hangingwall

6.3.3 Rock Properties

For each rock type, the undisturbed and disturbed rock mass values have been calculated using the Hoek-Brown Failure Criterion and the Mohr-Coulomb Failure Criterion. The rock mass for the case study area has been assumed to be in the undisturbed category. The Hoek-Brown Failure Criterion values were used to represent the rock mass, as opposed to the Mohr-Coulomb values.

The *intact* versus *rock mass* rock property values have been determined for the Creighton Mine case study area. These values are listed in Table 6-2. These rock properties have been defined from two main sources: from previous numerical modelling studies both at Creighton Mine and at other INCO mining properties, and from geomechanical laboratory testing. Note that these values were not used in the MINE2D modelling; these values were used in the initial FLAC numerical modelling. By the end of the calibration process, (using FLAC) these input parameters had been further refined in order to reflect the field data and BEM3D modelling.

ROCK TYPE	INTACT PROPERTIES	ROCK MASS PROPERTIES
Ore Zone: Massive Sulphides	E = 68.0 GPa ν = 0.25 C_o = 130 MPa m = 17.0 s = 1.0 density = 3000 kg/m^3 cohesion = 33.8 MPa ϕ = 35°	E = 23.7 GPa ν = 0.25 C_o = 57.4 MPa m = 4.87 s = 0.02047 RMR = 65 cohesion = 15.5 MPa ϕ = 33.26°
Norites	E = 79.0 GPa ν = 0.29 C_o = 155 MPa m = 17.0 s = 1.0 density = 2950 kg/m^3 cohesion = 36.2 MPa ϕ = 40°	E = 22.18 GPa ν = 0.29 C_o = 63.2 MPa m = 4.87 s = 0.0205 RMR = 65 cohesion = 16.5 MPa ϕ = 35°
Granites	E = 55.0 GPa ν = 0.25 C_o = 240 MPa m = 25.0 s = 1.0 density = 3000 kg/m^3 cohesion = 49.7 MPa ϕ = 45°	E = 25.1 GPa ν = 0.25 C_o = 97.8 MPa m = 7.42 s = 0.0229 RMR = 66 cohesion = 21.8 MPa ϕ = 42°

Table 6-2 Rock Properties

This resulting set of input data, that was determined from the FLAC calibration modelling, was subsequently used in the initial MINE2D cross-sectional model.

The input parameters, listed in Table 6-3, represent the both the resulting parameters determined from FLAC and the initial values used in the MINE2D modelling.

	ROCK PROPERTIES:
Ore Zone	E = 68.0 GPa ν = 0.25 T_o = 0.0 MPa C_o = 84.533 MPa (12260 psi) Cohesion = 22 MPa ϕ = 35°
Norites (hangingwall)	E = 79.0 GPa ν = 0.29 T_o = 0.0 MPa C_o = 103.91 MPa (15070 psi) Cohesion = 30 MPa ϕ = 30°
Granites (footwall)	E = 55.0 GPa ν = 0.25 T_o = 0.0 MPa C_o = 76.81 MPa (11140 psi) Cohesion = 20 MPa ϕ = 35°

Table 6-3 Input Parameters for the MINE2D Cross-Section Model

6.3.4 Backfill Properties

The MINE2D numerical model requires the inclusion of backfill (or support pressures) in the excavations in order to more accurately represent the case study site.

As with the FLAC modelling, the excavations were mined using the rib pillar, cut-and-fill method; therefore, the input parameters for the modelled backfill must accurately represent the backfill/rib pillar combination.

The input parameters for both the FLAC and the MINE2D calibration numerical models have been derived from some backfill testing and previous numerical modelling, (Landriault, D. and P. Oliver, "The Convergence Resistance of Mine Backfills", 1989).

The input parameters which represent the cemented hydraulic fill and rib pillar combination are listed in Table 6-4. These values are identical to the parameters used in the FLAC modelling of the cross-sectional geometry.

Rib Pillar & Hydraulic Backfill Combination- Input Parameters for the MINE2D Modelling
Elastic Properties- E = 0.69 GPa ν = 0.16 Additional Plastic Properties- Cohesive Strength = 3.93 MPa ϕ = 30° C_o = 13.6 MPa T_o = 0 MPa

Table 6-4 Rib Pillar/Backfill Properties for MINE2D Modelling

6.3.5 Field Stresses

The MINE2D program allows for two primary stress components within a model. As well, these stresses can be oriented in any direction within the model. However, unlike FLAC, the MINE2D model cannot account for the effect of gravity.

The stresses within the MINE2D model were assumed to be the far-field values. This is the same assumption that was used in the FLAC modelling. Furthermore, the stress values are the same for the FLAC and MINE2D models. It should be noted that the major principal stress, σ_1, is oriented at right-angles (into the page) and is not taken into account in the cross-sectional model.

For the MINE2D calibration modelling, the in-situ stress regime at the 6650 level is outlined in Table 6-5. The stresses in the cross-sectional model vary with depth at a rate of 1.304 psi/ft.

The vertical stress component in the cross-sectional model is equal to the σ_3 value in Table 6-5; likewise, the horizontal stress component is equal to the σ_2 value. Therefore, the stress regime represented in the cross-sectional model is hydrostatic.

	Magnitude MPa (psi)	Azimuth (in degrees)	Dip - down (in degrees)
σ_1	93.5 (13560)	100	0
σ_2	60.0 (8700)	190	-55
σ_3	60.0 (8700)	10	-35

Table 6-5 In-situ Stresses at the 6650 Level

6.4 Results

A cross-section through the case study site is representative of plane strain conditions. However, a model which accounts for only the mining in the 6600-6700 ore block would be inaccurate -- at least some of the upper and lower mining blocks should be taken into account. Therefore, a vertical cross-section, which is a simplification of the ore outline from the 6400 level to the 6800 level, has been used for the MINE2D modelling (see Figure 6-2).

Although the section from 6400 level to 6800 level allows for some of the pre-slot mining effects, it is obviously an abbreviated section through Creighton Mine. The actual mining extends upwards from the 6400 level by at least 450 feet. It is quite clear that these upper mining areas would effect the 6600-6700 ore block, yet, a section of the entire mine could not be modelled due to the sheer size of the problem. Although the MINE2D code is fully capable of modelling a huge cross-sectional area, it is the FLAC code which runs into difficulties as the model gets too large. Specifically, the problem is related to the FLAC grid.

The FLAC grid must encompass, not only the immediate mining area, but it must also encompass an area outside the mining. This surrounding grid area must be in the order of 8- to 10-times the largest mining span in order to eliminate the effects of the outer boundaries. This problem is not encountered with the MINE2D code because of the use of boundary elements. A large mining area, using FLAC, cannot be modelled with a fine grid for the reason of gross run-times. The alternative is to increase the size of each of the grid zones; however, with increasingly larger grid zones (and hence a coarser grid), the results of the model become less and less detailed.

This is an important factor to consider when very detailed results are required for specific areas. In particular, a fair amount of detail is required for the determination of a failure zone in the crown pillar. A model of the entire mine, whereby the crown is a comparatively small area, will not allow for detailed results due to the required coarse grid. For this reason, the FLAC model was created for the ore zone area from 6400 level to 6800 level. This section allows adequate run times and somewhat detailed results in the crown.

The reason that the entire section was not modelled with MINE2D is because of the required comparison to FLAC. FLAC is the limiting factor in that it can only model a smaller area of the mine. The modeller immediately realizes, however, that this smaller cross-section model will develop inaccuracies because of the lost effects of the upper country mining. This fact is important to keep in mind when reviewing the results of the modelling.

A closer examination of the ore zone from the 6400 level to the 6800 level in cross-section still yields a fairly complex geometry. The western part of the ore zone above 6600 level is much wider, from hangingwall to footwall, than the eastern section. The slot itself is located at the eastern side of the ore zone.

The variation in the ore geometry within the 6400-6800 block is not a favourable condition for 2D modelling due to the unfulfilled plane strain conditions. However, an attempt at calibration modelling was made for the western side of the zone since this area has been well-documented regarding the actual failure of the crown.

The mining sequence for the ore blocks located between 6400 level and 6800 level is represented in the cross-section model, see Figure 6-3. This sequence is further defined within Table 6-6.

step 1	- mining of the upper ore block (6400-6600 level) - backfilling using stiff fill
step 2	- mining of the lower ore block (6700-6800 level) - backfilling using stiff fill
steps 3-9	- mining from 6700 towards 6600 level (4300 ore block), using 20 foot (6 metre) vertical slices - backfilling using stiff fill

Table 6-6 Mining Sequence for Cross-Section Modelling

Note that the cross-sectional model does not take the mining of the destress slot into account. Only the known failure of the western section of the crown pillar has been used in the calibration. This assumed failure was also used in the calibration of the FLAC numerical models.

The mining steps used in the modelling are further detailed:

6400-6600 Ore Block- The ore block, in cross section, is fairly uniform on the western part of the ore body. The approximate width of the ore zone in this region, from footwall to hangingwall, is 137 metres (450 feet).

6700-6800 Ore Block- The geometry of this ore block is uniform; the average width (from footwall to hangingwall) is 60.9 metres (200 feet) on both the 6700 and 6800 levels.

4300 Ore Block- The mining above 6700 level in the western region of the ore zone is referred to as the 4300 Ore Block. The average width of the zone, from the footwall to the hangingwall is 60 metres (200 feet).

A summary of the mining dimensions used in the cross-sectional MINE2D model is provided in Table 6-7.

	Width in metres (feet)	Height in metres (feet)
6400-6600 Ore Block	122 (400)	54.8 (180)
6700-6800 Ore Block	61 (200)	26.5 (87)
4300 Ore Block	61 (200)	42.67 (140*) 6 metre slices

* Note: this is the distance between 6700 Level and 6600 Level (the total height of the crown pillar).

Table 6-7 Dimensions of the Mining Blocks in the MINE2D Vertical Cross-Section Model

After the upper and lower mining blocks had been completely excavated in the model, the mining of the 4300 ore block was commenced. The cross-sectional model has simulated the 4300 mining with a progressive series of vertical slices, each being 6.1 metres in height.

All of the actual underground mining was executed using mechanised cut-and-fill methods with transverse rib pillars as support. Therefore, input parameters are required for the rib pillar and backfill combination. The values that were used in the FLAC model were also used in the MINE2D cross-section modelling, refer to Table 6-4.

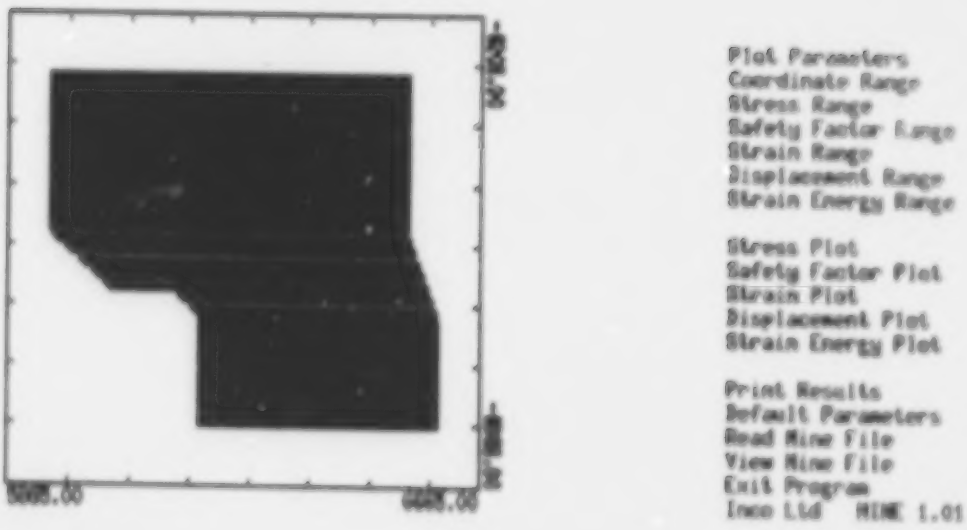

Figure 6-2 MINE2D MODEL.

- Vertical Cross-Section of Creighton Mine.
- Simulating Mining From 6400 Level - 6500 Level.

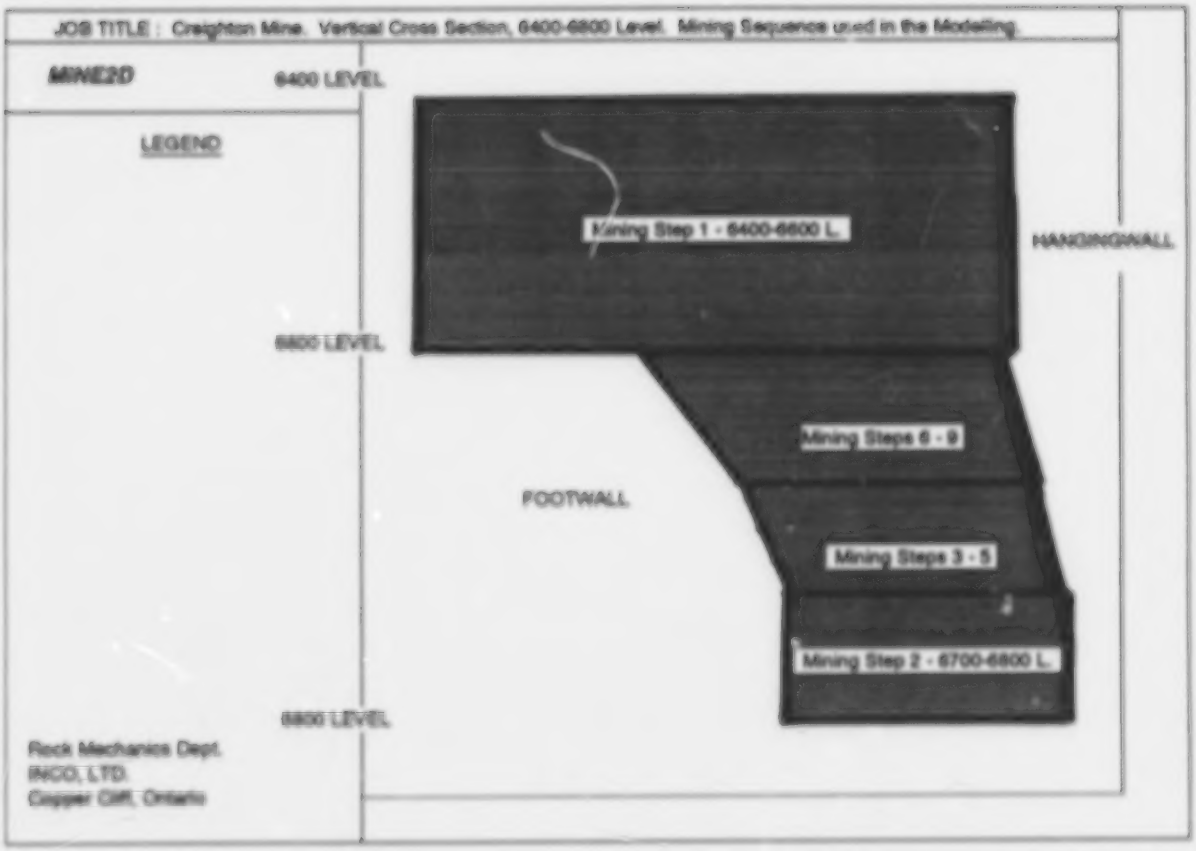

Figure 6-3 Mining Sequence, Cross-Section MINE2D Model (from 6400 Level to 6800 Level, Creighton Mine)

The calibration of the model has been carried-out such that the results of the vertical cross-section were compared to the known ground behaviour of the case study site. Specifically, there is documentation for the time of crown pillar failure: following the mining of the first VRM panel and the mining of the 4300 Ore Block, a large rock burst occurred below the 6600 level. The crown pillar at this time had been excavated up to an approximate vertical height of 27 metres (90 feet). This height of 27 metres was the assumed height for failure of the crown pillar and is subsequently the value used for the calibration of the MINE2D model.

The calibration techniques and results are discussed in detail in the following sections.

6.4.1 Model Run #1: Elastic, Boundary Element Modelling, BEM2D

The numerical modelling code, BEM2D, was initially used to model the opening shapes for a quick appraisal of the expected ground behaviour.

This model did not include any fill material or pressure in the excavations. As well, the model included only the mining of the 6400-6600 ore block and the 6700-6800 ore block; the crown pillar had a thickness of 42.76 metres (140 feet).

The BEM2D model is limited to a single material property which behaves elastically. Referring to the Table 6-4, the properties describing the norites were used as input into the model. The stresses were set according to the Table 6-2, that is, with a hydrostatic stress field and increasing stresses (1.304 psi per foot of depth).

The results of this first modelling run are represented with the following three figures: Figure 6-4 is a Safety Factor Contour plot, Figure 6-5 is a plot of the Sigma 1 stress contours, and Figure 6-6 is a plot of the Sigma 3 stress contours.

These results indicate that the crown pillar is failing under tension. The tensile failure within the Figure 6-6 (Sigma 3) is in the range of 1000 psi, or 6.895 MPa. However, it should be noted that tensile failure was not observed underground. This suggests that the excavations within the models require some additional internal pressure in order to more accurately represent the ground conditions.

Another BEM2D elastic run is necessary to determine the effect of using support pressures in place of backfill. The value of 1000 psi will be a starting point for internal support pressures within the mechanised cut-and-fill excavations. The results of this numerical modelling study are detailed in the following section, 6.3.3.2 for Model Run #2 using BEM2D, Elastic.

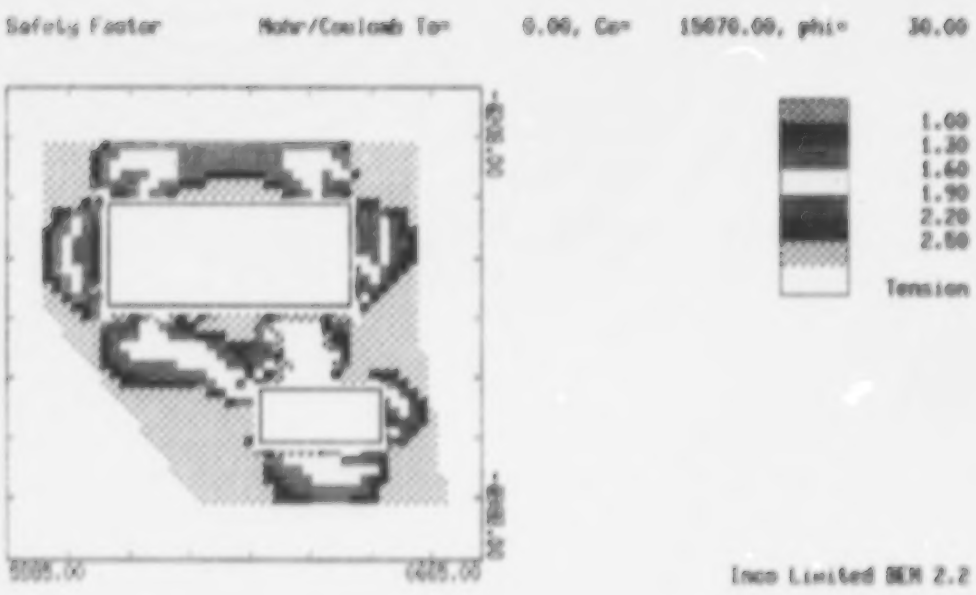

Figure 6-4 SAFETY FACTOR CONTOUR PLOT.

- Model Run #1. BEM2D Elastic.
- No Backfill.
- No Support Pressures.
- Crown Pillar Thickness is 140 feet.

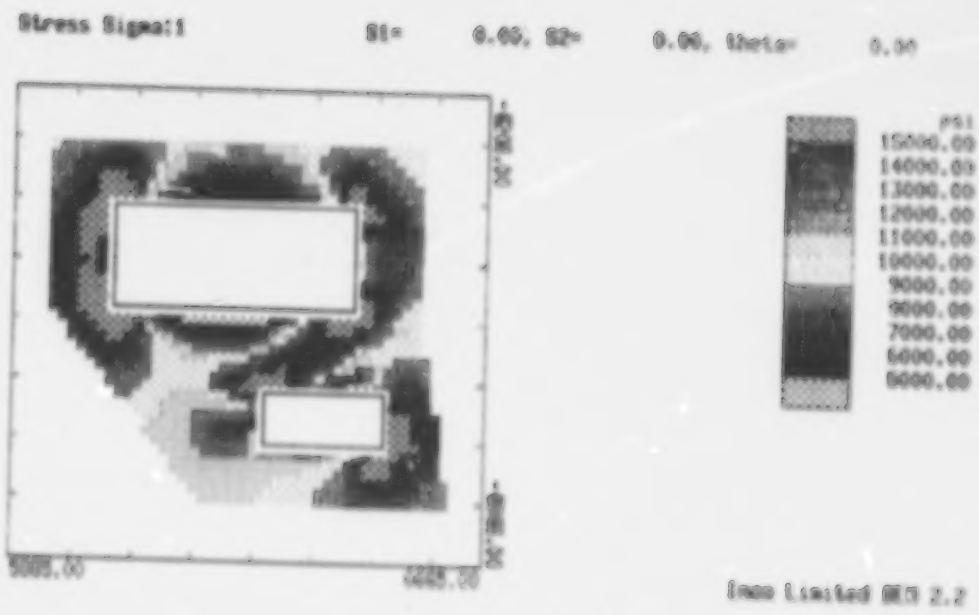

Figure 6-5 SIGMA 1: STRESS CONTOUR PLOT.

- Model Run #1. BEM2D Elastic.
- No Backfill.
- No Support Pressures.
- Crown Pillar Thickness is 140 feet.

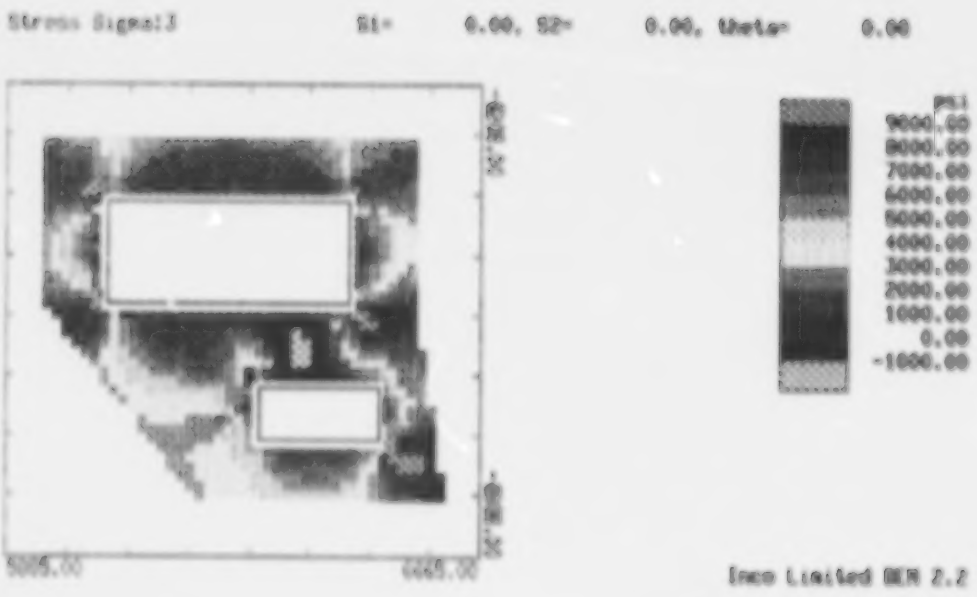

Figure 6-6 SIGMA 3: STRESS CONTOUR PLOT.

- Model Run #1. BEM2D Elastic.
- No Backfill.
- No Support Pressures.
- Crown Pillar Thickness is 140 feet.

6.4.2 Model Run #2: Elastic, Boundary Element Modelling, BEM2D

The second model was required in order to take into account the effect of the rib pillars and hydraulic backfill in the mechanised cut-and-fill stopes.

The rib pillars are transverse, but they are also discontinuous at some point in-between the hangingwall and footwall. A mid-span slot was driven through each of the transverse rib pillars. However, in the vertical extent, these pillars are continuous. From this information, it can be reasonably assumed that the rib pillars will carry more load, and allow a greater amount of stress transfer, in the vertical direction than they will in the horizontal sense.

In fact, the internal support pressures within the excavations should be greater in the vertical direction than in the horizontal direction in order to more accurately represent the rock mass behaviour and the mining.

There is a lack of data to suggest by how much the rib support is reduced in the lateral direction. However, it has been previously assumed that the vertical load carrying capacity of the pillars is twice as great as the horizontal capacity (Wiles, 1990). However, this is just an assumption. In reality, these pillars should be fully modelled in order to ascertain a more determinate relationship between the vertical and horizontal load carrying capacities of the pillars.

The second model was run with almost identical input parameters to the first run. The geometry was slightly changed in order to further the state of mining to where the crown pillar was extracted to a vertical height of 30.5 metres (100 feet). At this point, the crown is at the expected threshold of failure (the 27 metre/90 foot failure). The stress field and the rock properties were identical to the previous modelling, Run #1.

The initial support pressures within the excavations were set at 1000 psi in the vertical direction and 500 psi in the horizontal direction. The results of this second model, with the 1000 psi versus 500 psi support pressures, were similar to the results of Run #1 -- a large zone of tensile failure was predicted in the centre of the crown pillar.

This BEM2D model was re-run several times whereby each successive run used progressively higher support pressures in order to reduce the zone of tensile failure.

The final run simulated support pressures of 2000 psi in the vertical direction and 1000 psi in the horizontal direction. The results are represented in Figure 6-7 (Safety Factor Plot), Figure 6-8 (Sigma 1 Plot) and Figure 6-9 (Sigma 3 Plot).

The safety factor plot, Figure 6-7, indicates only a minimal region of tensile failure within the 100 foot crown. The main region of potential failure, other than the insignificant zone of tensile failure, is indicated as a shear-type failure. This failure is represented in the Safety Factor Plot for the range of safety values between 1.0 and 1.3. Refer to Section 4 of this calibration volume for a detailed explanation of Estimating the Stress Relaxation Zone with BEM3D. BEM3D is the 3-dimensional version of the BEM2D program. The safety factor limits, as used with the BEM3D, are also pertinent to the BEM2D modelling.

The failure in this model is predicted in a shearing configuration. The shear extends from the top, left-hand corner of the 6700-6800 ore block (at the footwall contact) up to the bottom, right-hand corner of the 6600 level mining unit (at the hangingwall contact).

The BEM2D data file representing this final elastic, boundary element model is listed in Appendix D. These elastic, boundary element models give an idea of the required input parameters in order to echo the known response of the rock mass.

A comparison to the boundary element, elastic code was the next step in the calibration process. These results are contained in the following section 6.3.3.4 using the MINE2D code with the elastic capabilities.

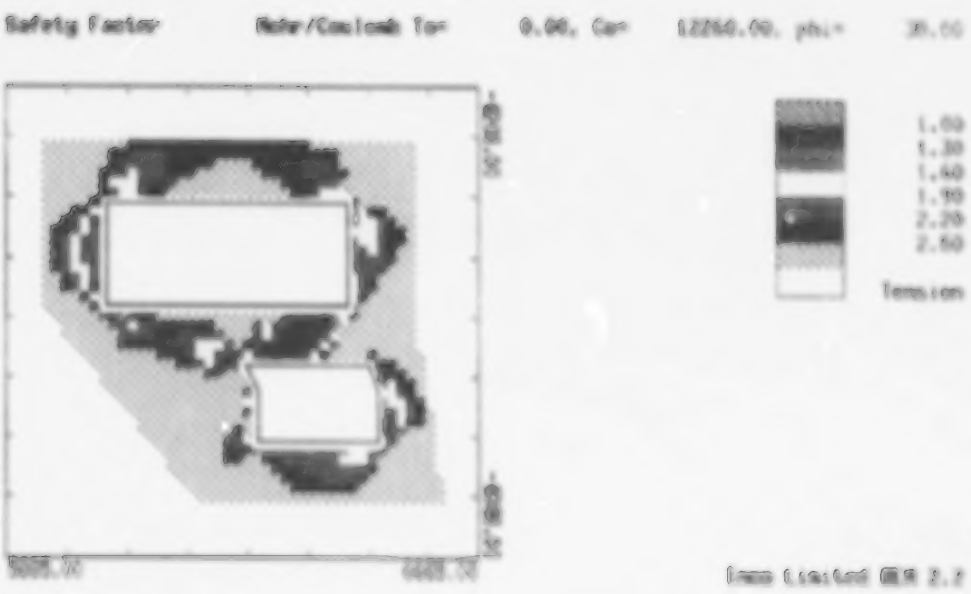

Figure 6-7 SAFETY FACTOR CONTOUR PLOT.

- Model Run #2. BEM2D Elastic.
- No Backfill.
- Support Pressures: V=2000 psi & H=1000 psi
- Crown Pillar Thickness is 100 feet.

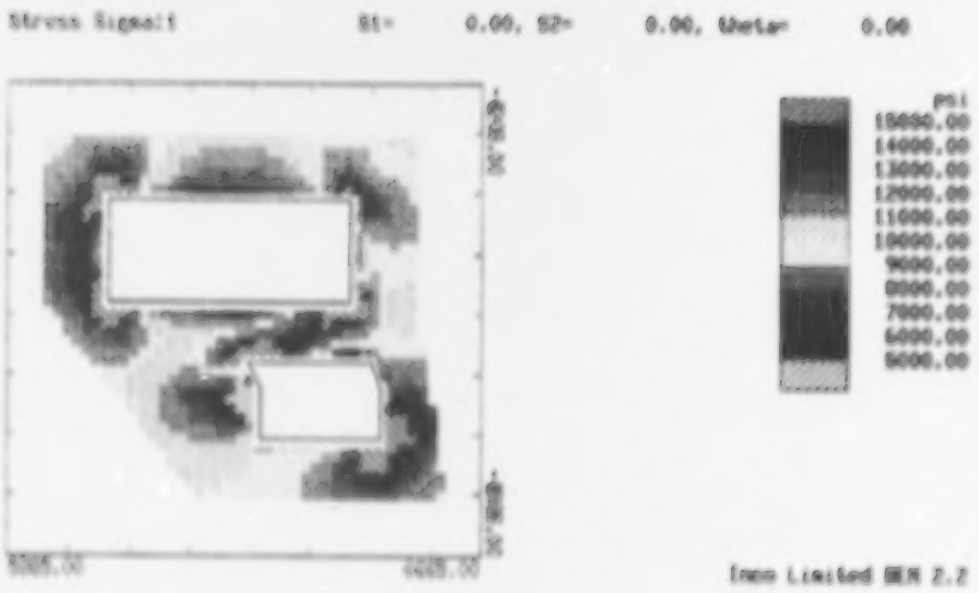

Figure 6-8 SIGMA 1: STRESS CONTOUR PLOT.

- Model Run #2. BEM2D Elastic.
- No Backfill.
- Support Pressures: V=2000 psi & H=1000 psi
- Crown Pillar Thickness is 100 feet.

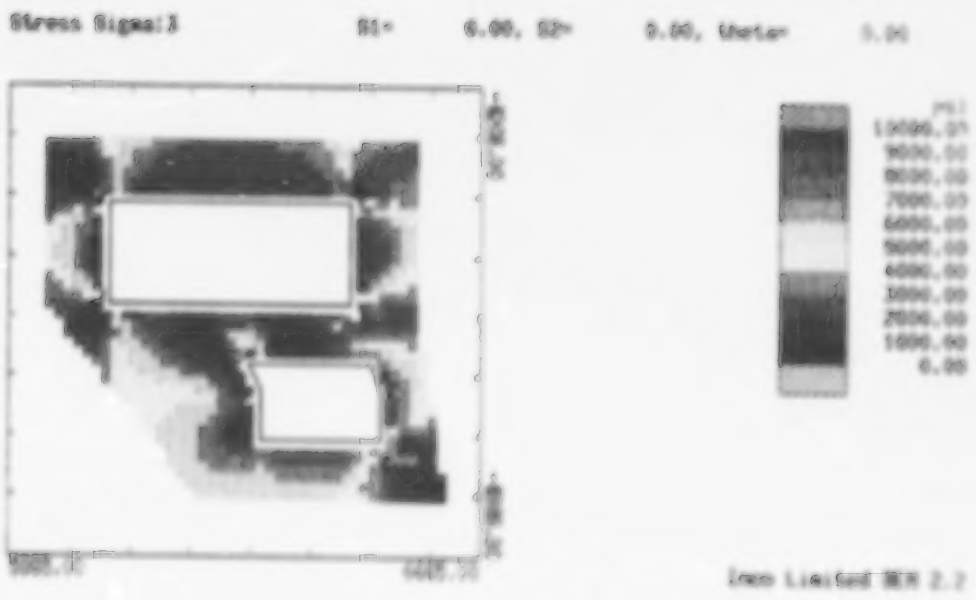

Figure 6-9 SIGMA 3: STRESS CONTOUR PLOT.

- Model Run #2. BEM2D Elastic.
- No Backfill.
- Support Pressures: V=2000 psi & H=1000 psi
- Crown Pillar Thickness is 100 feet.

6.4.3 Model Run #3: Elastic, Boundary Element Modelling, MINE2D

The Model Run #1 was repeated using the MINE2D code with the elastic criterion. The input parameters were identical to the BEM2D run and there was also the zero fill pressure within the excavations. The results of this MINE2D run were highly comparable to the results of the BEM2D model.

The Safety Factor Plot, Sigma 1 Plot, and the Sigma 2 Plot are represented in Figure 6-10, Figure 6-11, and Figure 6-12, respectively. These plots are almost identical to the BEM2D results (refer to the previous BEM2D stress plots documented in Figure 6-5 and Figure 6-6; as well refer to the factor of safety plot of the BEM2D results in Figure 6-4).

This sequence of modelling clearly demonstrates that MINE2D can be used as an elastic boundary element model for the preliminary investigation of a modelling problem. The small differences which can be seen on close inspection relate primarily to the opening corners. MINE2D predicts the possibility of slightly more failure and more tension than is indicated by the BEM2D model.

A supplementary facet of the MINE2D is the capability of showing displacements. The x- and y-displacements have been plotted and are represented in Figure 6-13 and Figure 6-14, respectively. It was through viewing these displacement plots that an understanding could be arrived at for the cause of the tensile stresses in the crown pillar, as described:

- upon excavation of the 6400-6600 ore block, convergence of the stope walls commences. The base of the mining unit also undergoes convergence whereby the base of the excavation begins to move upwards. This long span along the base of the 6600 level mining allows sufficient uplift to occur, and subsequently, tension in the crown pillar is developed.

A further modelling study using the MINE2D program was carried-out whereby the effect of the support pressures with a MINE2D model was compared to the results of the BEM2D model also simulating support pressures. These results are outlined in the next section 6.3.3.4.

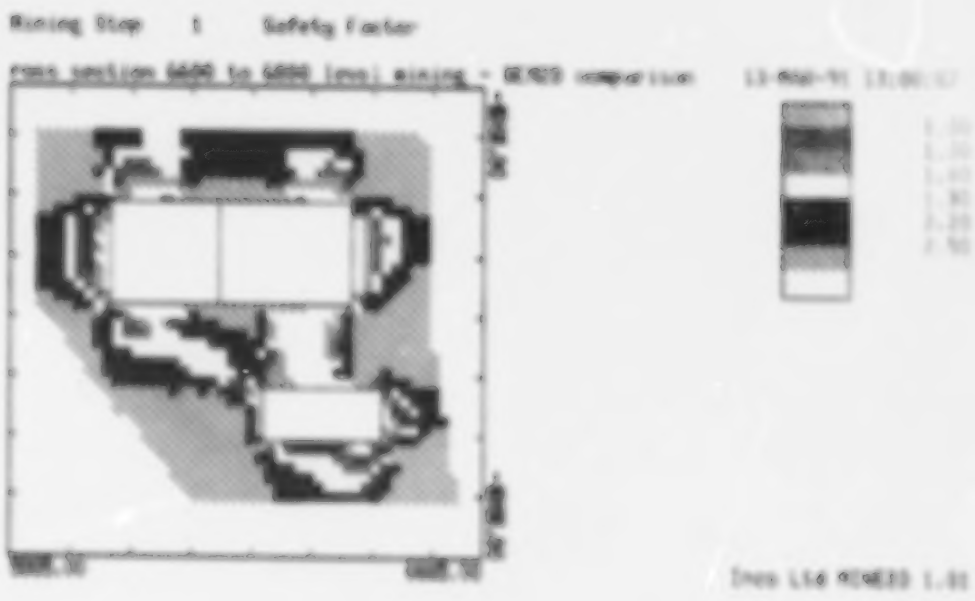

Figure 6-10 SAFETY FACTOR CONTOUR PLOT.

- Model Run #3. MINE2D Elastic.
- No Backfill.
- No Support Pressures.
- Crown Pillar Thickness is 160 feet.

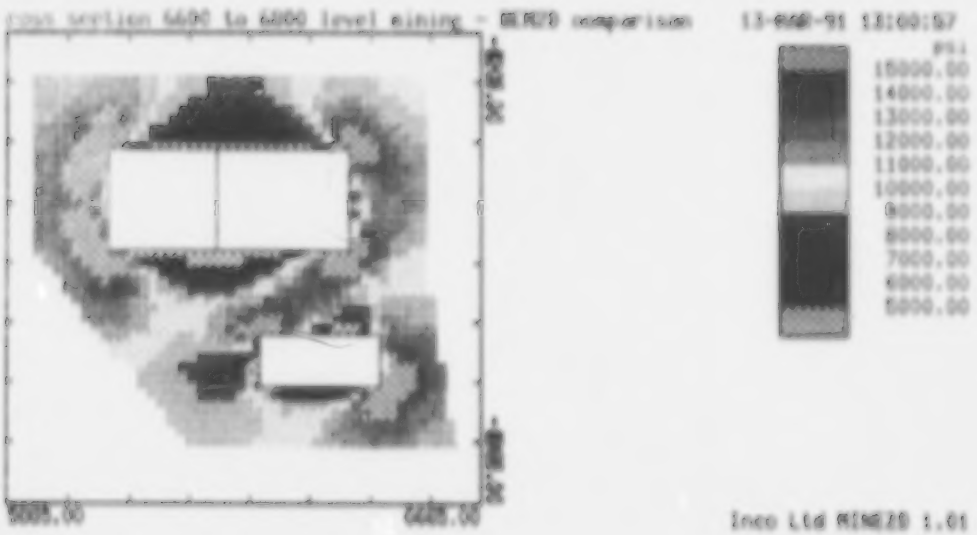

Figure 6-11 SIGMA 1: STRESS CONTOUR PLOT.

- Model Run #3. MINE2D Elastic.
- No Backfill.
- No Support Pressures.
- Crown Pillar Thickness is 140 feet.

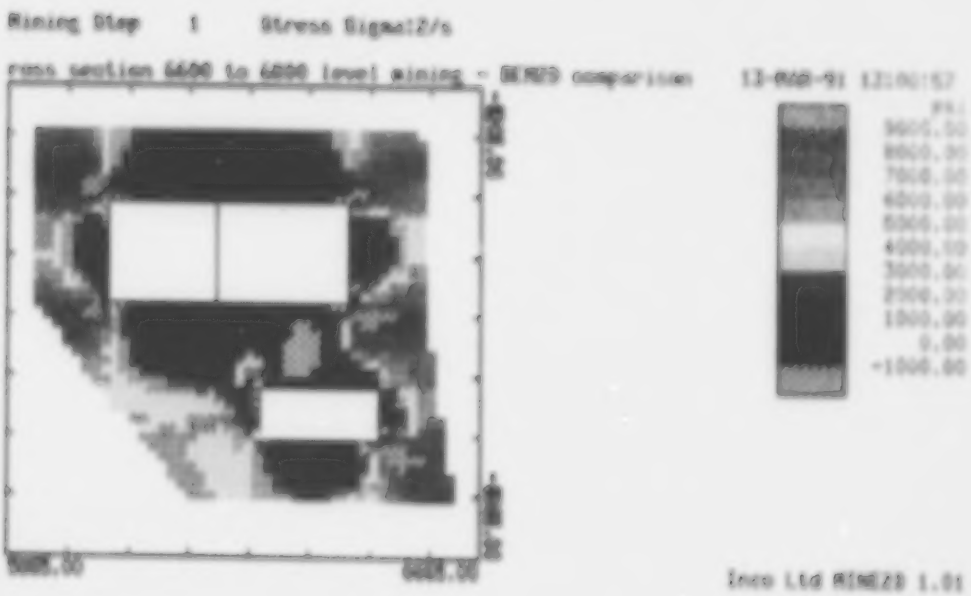
Mining Step 1 Stress Sigma1/s
cross section 6600 to 6800 level mining - MINE2D comparison
13-AUG-91 12:00:57
Inco Ltd MINE2D 1.01

Figure 6-12 SIGMA 2: STRESS CONTOUR PLOT.

- Model Run #3. MINE2D Elastic.
- No Backfill.
- No Support Pressures.
- Crown Pillar Thickness is 140 feet.

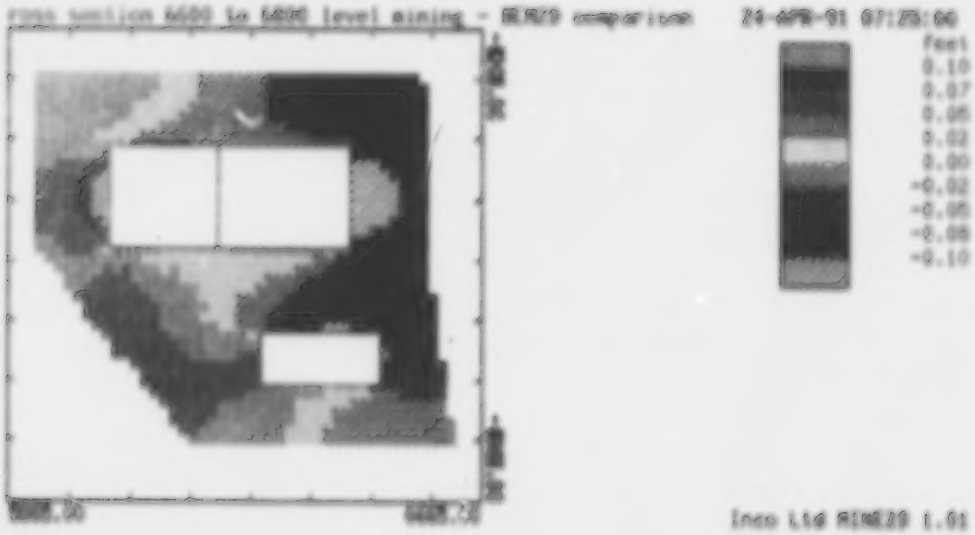

Figure 6-13 X-DISPLACEMENT PLOT.

- Model Run #3. MINE2D Elastic.
- No. Backfill.
- No Support Pressures.
- Crown Pillar Thickness is 140 feet.

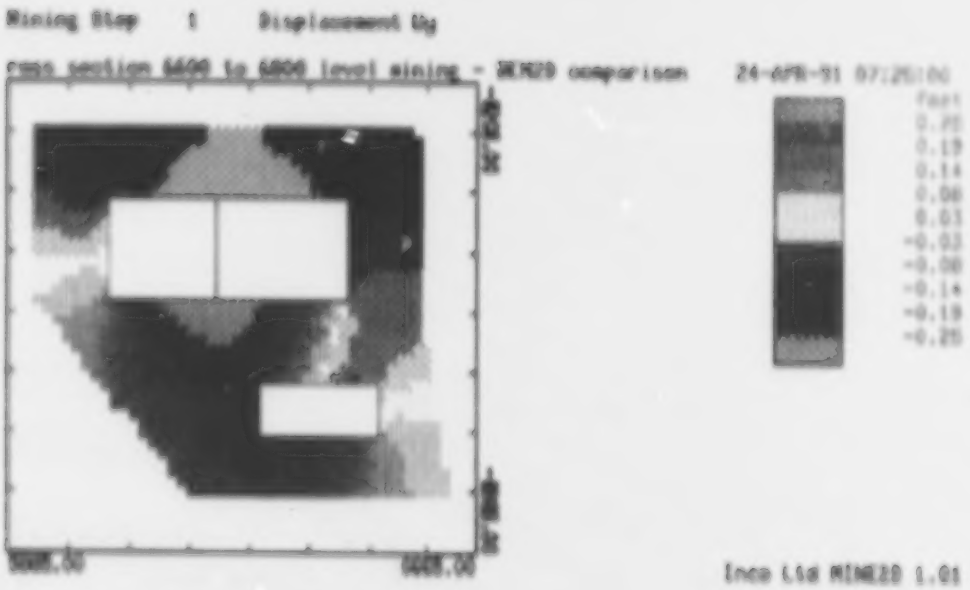

Figure 6-14 Y-DISPLACEMENT PLOT.

- Model Run #3. MINE2D Elastic.
- No Backfill.
- No Support Pressures.
- Crown Piller Thickness is 140 feet.

6.4.4 Model Run #4: Elastic, Boundary Element Modelling, MINE2D

The Model Run #2 (BEM2D) was re-run using the MINE2D program. The same input values for the geometry, the stresses and the material properties (Norites, from Table 6-4) were used.

Additionally, the same support pressures were employed with the MINE2D code as were used in the BEM2D model. A 2000 psi support pressure was applied in the vertical direction of the model and the 1000 psi support pressure was applied in the horizontal plane.

The results of the MINE2D modelling are presented in Figure 6-15 for the Safety Factor Plot, Figure 6-16 for the Sigma 1 Plot, and Figure 6-17 for the Sigma 2 Plot.

The plots for this MINE2D model are quite similar to those of the BEM2D modelling. The primary differences between the modelling results is the prediction of slightly more failure with the MINE2D model. In particular, there is a greater amount of failure indicated about the corners of the openings and also about the footwall nose in the top left-corner of the 6700-6800 ore block.

This discrepancy in the failure zone predictions can be attributed to the way in which the pressures are applied within the two programs. With the MINE2D code, the support pressures are applied in a strictly horizontal and vertical manner. Contrarily, the BEM2D program applies the support pressures at right-angles to the excavation walls, including any inclined surfaces.

In the case of the inclined surfaces in the BEM2D model, the user would have to calculate the equivalent normal and shear stress components which would result in having pressures of 1000 psi horizontally and 2000 psi vertically.

For this particular modelling run using MINE2D, the normal and shear stress calculation was not deemed necessary. The primary purpose of this run was to obtain a cursory comparison of these MINE2D results with the previous BEM2D modelling, using the identical modelling set-up.

One more elastic run was made with the MINE2D program. This model was used to determine the effect of using pressurized fill in the excavations instead of the support pressures. The results are detailed in the following section 6.3.3.5.

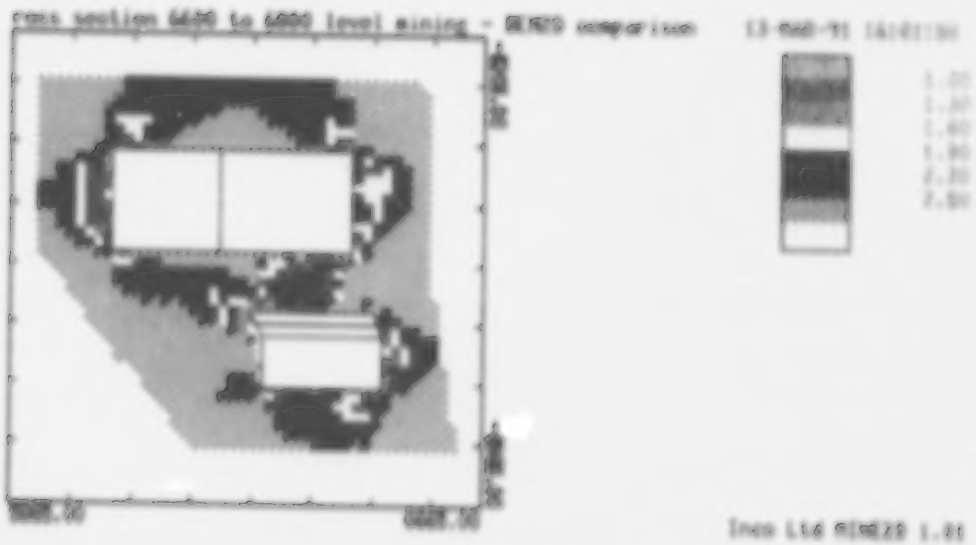

Figure 6-15 SAFETY FACTOR CONTOUR PLOT.

- Model Run #4. MINE2D Elastic.
- No Backfill.
- Support Pressures: V=2000 psi & H=1000 psi
- Crown Pillar Thickness is 100 feet.

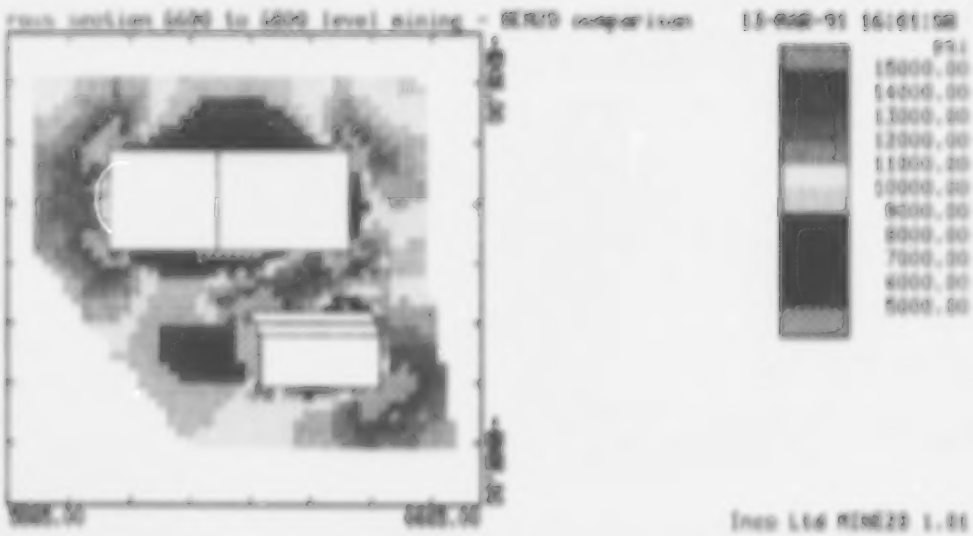

Figure 6-10 SIGMA 1: STRESS CONTOUR PLOT.

- Model Run #4. MINE2D Elastic.
- No Backfill.
- Support Pressures: V=2000 psi & H=1000 psi
- Crown Pillar Thickness is 100 feet.

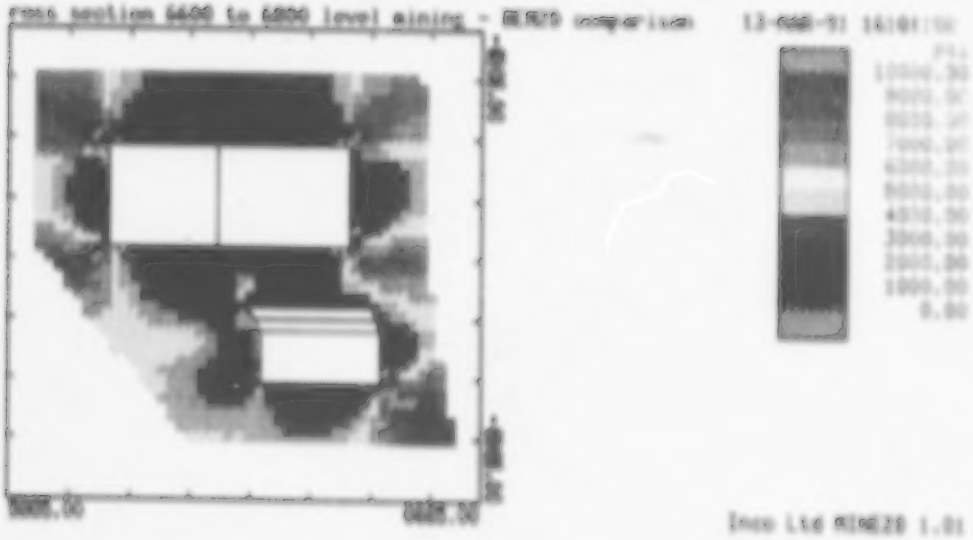

Figure 6-17 SIGMA 2: STRESS CONTOUR PLOT.

- Model Run 04. MINE2D Elastic.
- No Backfill.
- Support Pressures: V=2000 psi & H=1000 psi
- Crown Piller Thickness is 100 feet.

6.4.5 Model Run #5: Elastic, Boundary Element Modelling, MINE2D

A third and final elastic run was made with the MINE2D program in order to determine the effect of using pressurized fill in the excavations as opposed to using the support pressures.

In the model, all of the input parameters were identical to the previous numerical modelling runs. The only difference with this run was the use of backfill and initialized pressures within the backfill instead of support pressures.

This modelling approach allows the pressurized fill to undergo adjustment as the solution converges. Subsequently, this allows for a variation in the distribution of pressures within the backfill as the model comes to equilibrium. This is unlike the previous models in which the support pressures remained constant throughout the modelling.

There has been some concern expressed by the author of the MINE2D code, Dr. Wiles, regarding the validity of replacing the ore with backfill. Specifically, it is not clear whether the model can realistically simulate backfill behaviour in the corners of the excavation.

The recommended approach given by Dr. Wiles is to first excavate an opening and apply support pressures to the excavation walls. When the model has been brought to equilibrium, the support pressures are removed and simultaneously replaced with a backfill material. The backfill material should have identical internal pressures. The modelling can then proceed to the next stage of mining.

The results of the modelling are presented in Figure 6-18, Figure 6-19, and Figure 6-20. These plots correspond to the Factor of Safety Plot, the Sigma 1 Plot, and the Sigma 2 Plot, respectively.

An analysis of the results suggest that the non-recommended, direct, pressurized fill method predicts less failure. This method of simulating the mining and backfilling obviously demonstrates that there is a difference in the modelling results.

The MINE2D model, at this point, is deemed to be an accurate representation of the case study site. It has been determined that the MINE2D program is capable of simulating an elastic model; this was determined from the comparison of the BEM2D (elastic) modelling with the identical MINE2D set-up (also elastic). No further purely-elastic models were needed to be run with the MINE2D code for this calibration study.

The same set-up of the MINE2D elastic case study model has been carried-over into the elasto-visco-plasticity modelling using the same MINE2D program. The results of this additional MINE2D modelling are described in the following sections.

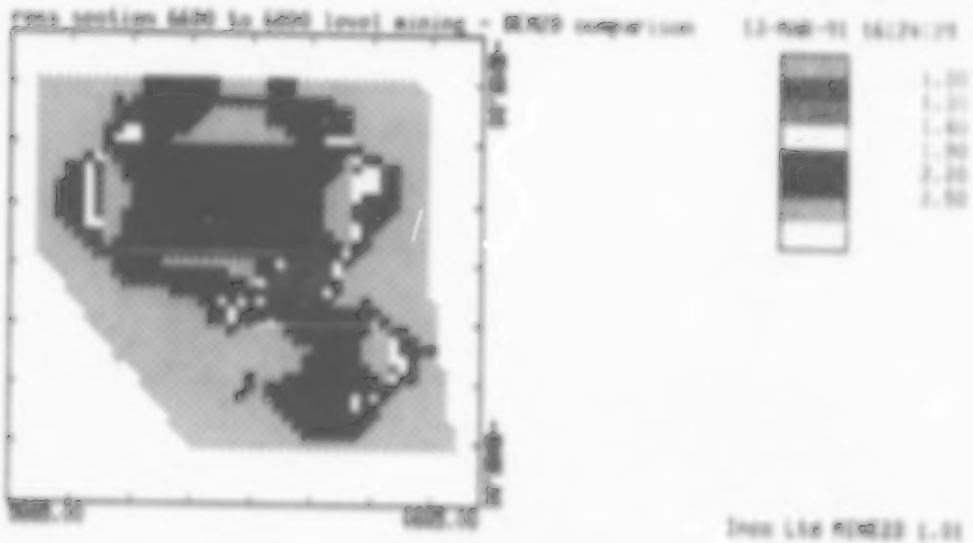

Figure 6-16 SAFETY FACTOR CONTOUR PLOT.

- Model Run 91. MINE3D Elastic.
- Pressurized Backfill.
- Crown Pillar Thickness is 100 feet.

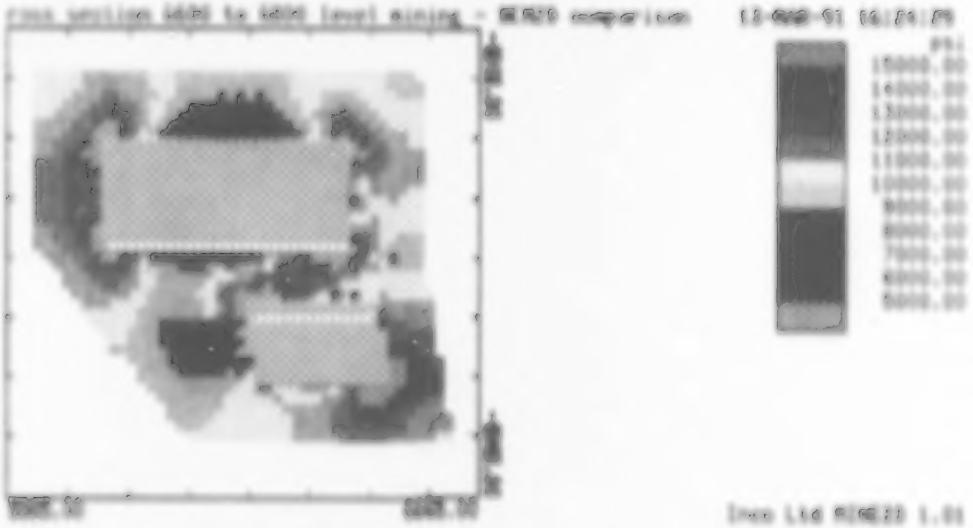

Figure 6-19 SIGMA 1: STRESS CONTOUR PLOT.

- Model Run 05. MINE2D Elastic.
- Precracked Backfill.
- Crown Piller Thickness is 100 feet.

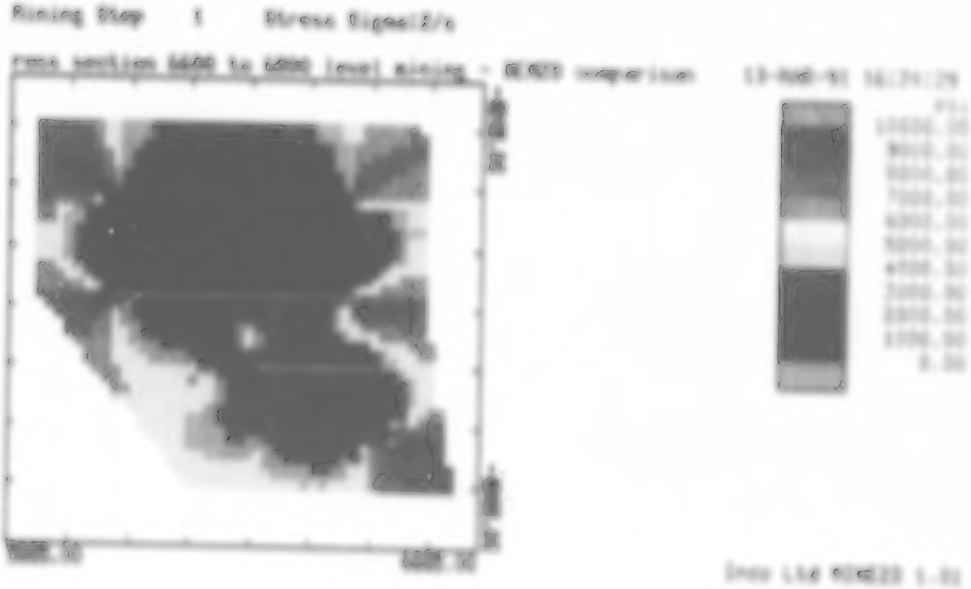

Figure 6-20 SIGMA 2: STRESS CONTOUR PLOT.

- Model Run 05. MINE2D Elastic.
- Pressurised Backfill.
- Crown Pillar Thickness is 100 feet.

6.4.6 Model Run #6: Plastic, Boundary Element Modelling, MINE2D

The first MINE2D elasto-visco-plasticity run was set-up with identical modelling geometry and stresses as the previous models. The support pressures, of 1000 psi horizontally and 2000 psi vertically, were also employed within the model.

The MINE2D code differs from the BEM2D program in that multiple materials can be simulated in the models. For this first plastic model, three distinct material zones were delineated: the massive sulphide ore zone, the hangingwall norites, and the footwall granites.

Each of the three material types were set up with identical properties as those used in the FLAC modelling. These values are represented in Table 6-6.

The excavation process in the model follows Dr. Wiles' recommendations:

- an area is excavated and specified support pressures are applied to the walls,
- the model is brought to equilibrium,
- the excavation is backfilled and pressurized (the pressures are equivalent to the specified support pressures),
- the model is again brought to equilibrium,
- this process is repeated for each of the mining steps.

For this model, an excavation is being backfilled at the same time that the next excavation is being mined. The validity of mining and filling in the same step was tested with this model. The results indicate that after filling an opening, the model requires only one iteration before the solution converges.

It should be noted that combining the filling procedure with a subsequent excavation step is only valid when the following condition is met: the specified internal pressures for both the excavation to be filled and for the new excavation must be equivalent to the specified initial fill pressures.

The results indicate that the crown pillar does not fail, even at a height of 24 metres (80 feet). The results have been plotted for the stage of mining where the crown pillar is at a vertical thickness of 60 feet. The results are represented in Figures which are contained in the following pages.

The first Figure 6-21 represents the plot of the mined and filled areas with the crown pillar thickness being 60 feet. The dark blue filled area indicates the host rock. The blue zone also represents the extent of the modelling area where the materials have been assigned plastic properties.

Outside of the blue area, the materials can only behave in an elastic manner. The yellow areas in the plot illustrate the backfilled stopes.

The Failure Zone Plot is represented in Figure 6-22; this is for an 80 foot (24 metre) crown pillar.

The red markings in the Failure Zone Plot indicate areas which are "currently yielding". Each red mark signifies a stress level which is equal to the strength limit of the material. The red marked area indicates that the material is behaving plastically. Any increase in sigma 1 or a decrease in sigma 3 will cause plastic strains to develop until conditions within the model return to equilibrium.

The blue markings in the Failure Zone Plot indicate areas which are "previously yielded". These areas indicate areas where the strength of the material in the blue area was exceeded either:

(i) in an earlier stage in the mining, or
(ii) in an earlier stage in the solution process for the current mining step.

Because of stress adjustments in the solution process, the stresses are currently less than the strength value and the material in the blue area is behaving in an elastic manner. In any subsequent mining stage, the material in the blue area can either behave elastically or plastically depending on the nature of the stress changes.

The magnitude of the plastic strains have been plotted and are shown in Figure 6-23. The plotted values are actually in micro-strains, and from the figure it can be concluded that strain magnitudes for this stage in the mining are very small. Note that the sign convention used for a strain plot is positive for compressive strains and negative for tensile strains.

With the same crown pillar height of 80 feet, the corresponding stress values have been plotted. Figure 6-24 represents the σ_1 contours and Figure 6-25 represents the σ_3 contours. These Figures indicate high stresses in the crown pillar and tensile stresses on the footwall-side of the 6700-6800 ore block.

It was deemed unnecessary to plot any of the results from the previous stages of mining for this model since the crown pillar had not failed even at a vertical height of 80 feet. Therefore, there is nothing worth seeing in the previous stages of the mining.

The following modelling run (#7) examines the effect of reducing the support pressures within the excavations. This is carried-out with the use of an identical plastic MINE2D model to model run #6.

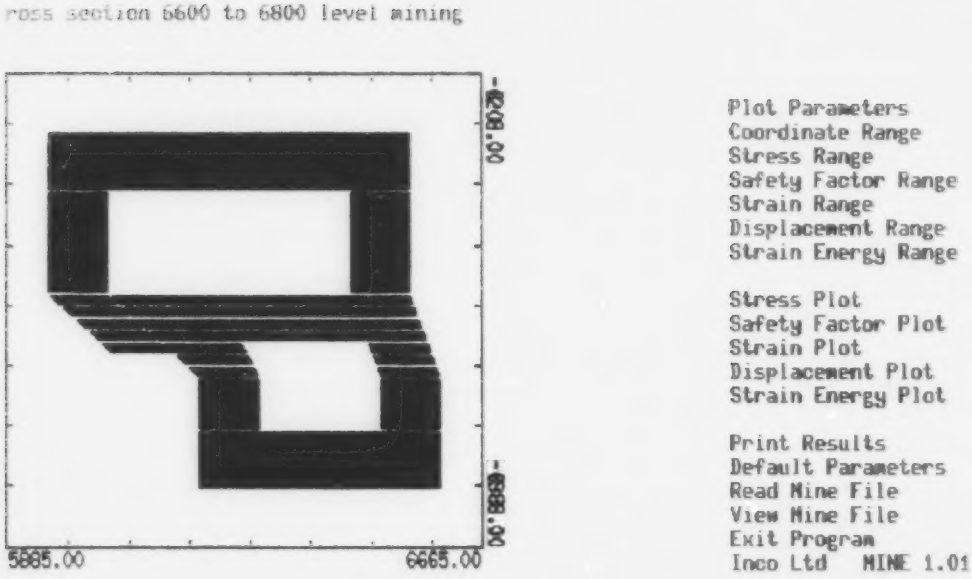

Figure 6-21 THE MINE2D MODEL INDICATING: MINED, FILLED AND INTACT AREAS.

- Model Run #6. MINE2D Plastic.
- No Backfill.
- Support Pressures: V=2000 psi & H=1000 psi
- Crown Pillar Thickness is 80 feet.

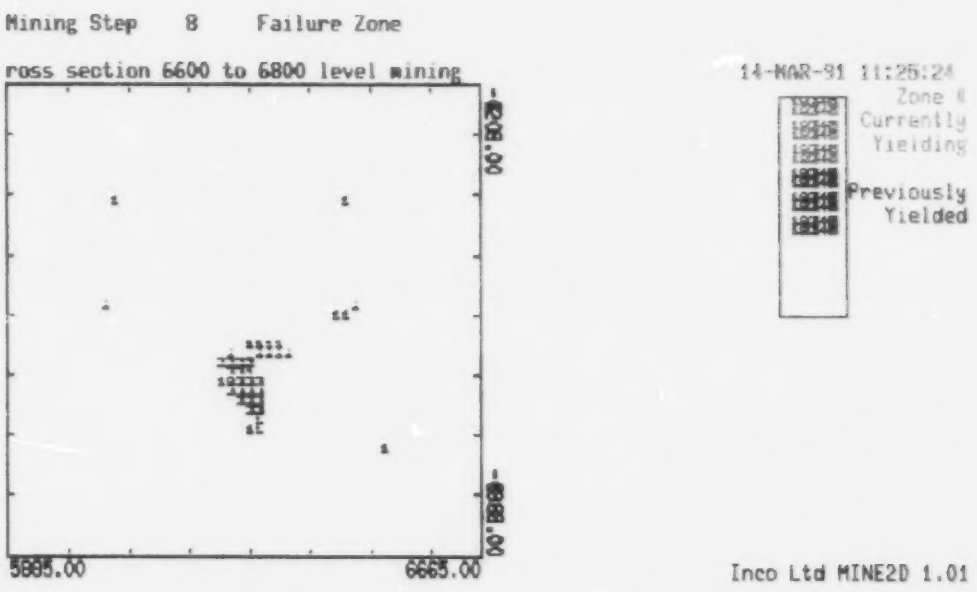

Figure 6-22 FAILURE ZONE PLOT.

- Model Run #6. MINE2D Plastic.
- No Backfill.
- Support Pressures: V=2000 psi & H=1000 psi
- Crown Pillar Thickness is 80 feet.

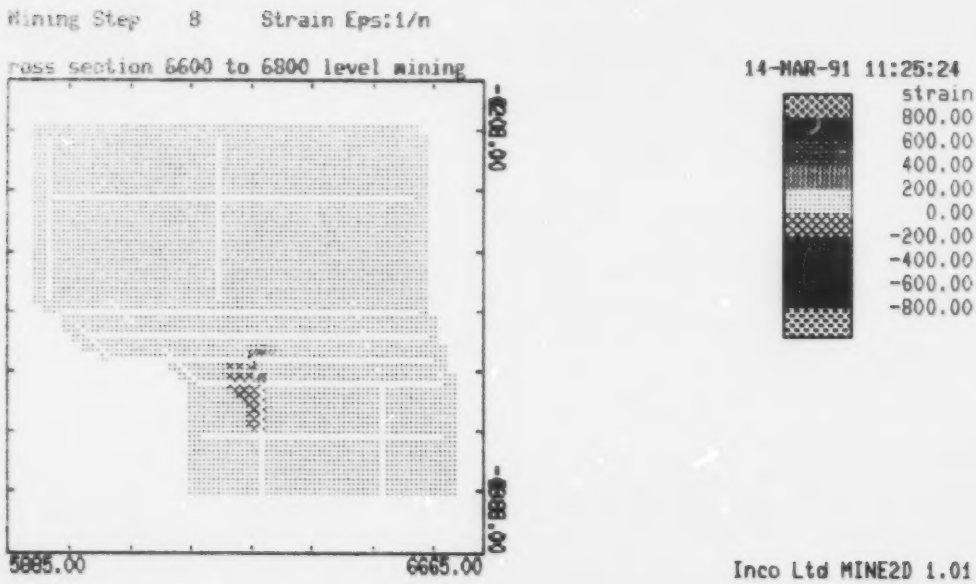

Figure 6-23 STRAIN PLOT.

- Model Run #6. MINE2D Plastic.
- No Backfill.
- Support Pressures: V=2000 psi & H=1000 psi
- Crown Pillar Thickness is 80 feet.

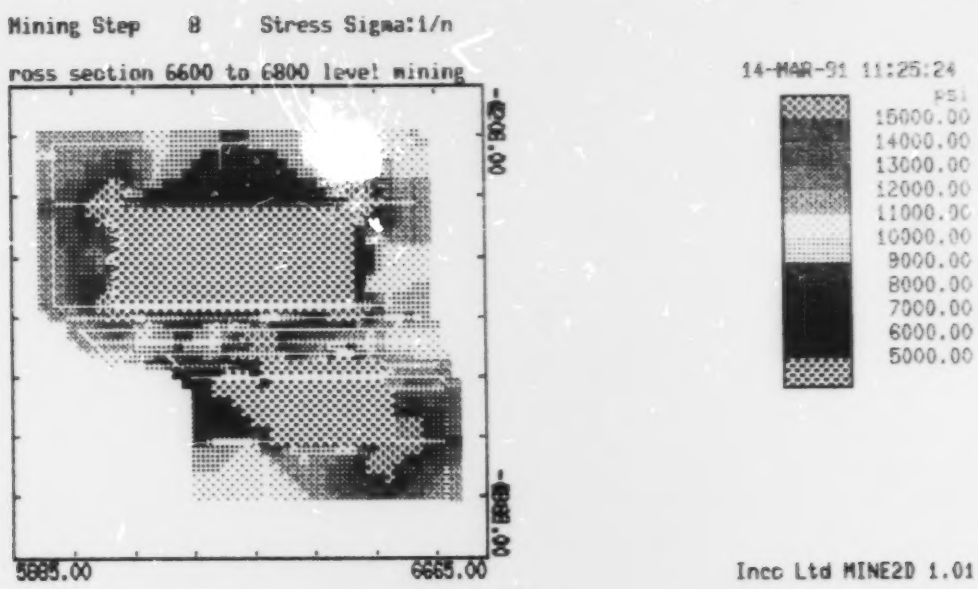

Figure 6-24 SIGMA 1: STRESS CONTOUR PLOT.

- Model Run #6. MINE2D Plastic.
- No Backfill.
- Support Pressures: V=2000 psi & H=1000 psi
- Crown Pillar Thickness is 80 feet.

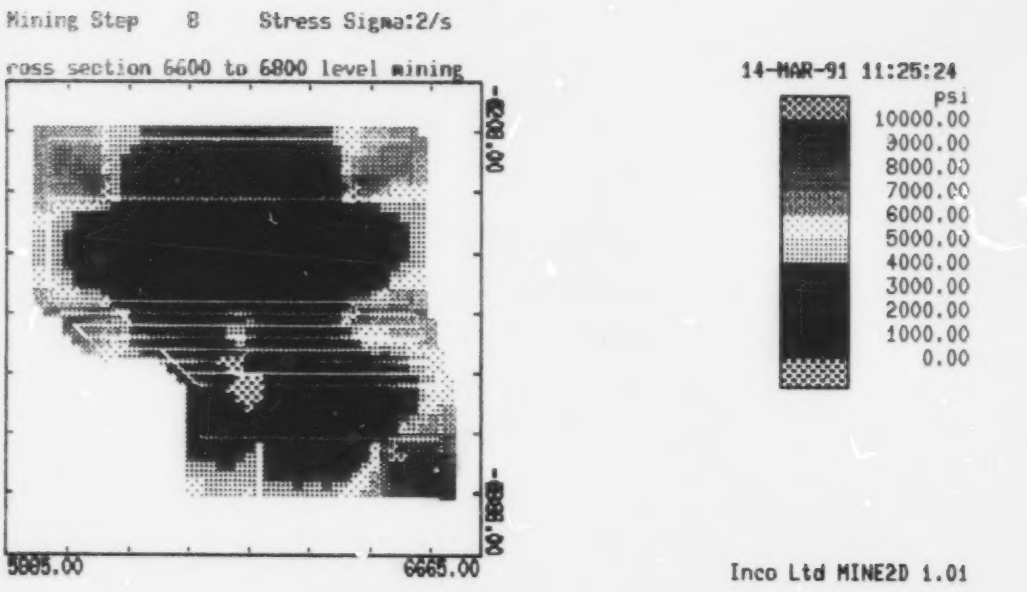

Figure 6-25 SIGMA 2: STRESS CONTOUR PLOT.

- Model Run #6. MINE2D Plastic.
- No Backfill.
- Support Pressures: V=2000 psi & H=1000 psi
- Crown Pillar Thickness is 80 feet.

6.4.7 Model Run #7: Plastic, Boundary Element Modelling, MINE2D

Another plastic, boundary element model was run using an identical set-up as the Model Run #6. The only difference with this second MINE2D plastic model is with the reduction in support pressures.

In place of the original horizontal pressure of 1000 psi, a lower value of 500 psi was used. Also, the vertical support pressure was halved from 2000 psi to 1000 psi. The change in support pressures required only a quick alteration to the data file. The stresses, for Material Type 5, were reduced to reflect the altered fill pressures. The data file for this modelling run is listed in Appendix E.

The mining steps associated with the extraction of both the 4300 ore block and some of the mining in the crown pillar have been plotted. Figure 6-26 represents the model for a 140 foot crown. Likewise, Figure 6-27 represents the plot with the 120 foot crown, Figure 6-28 is the 100 foot crown plot, and Figure 6-29 is the 80 foot crown plot.

As in the previous MINE2D modelling run, the dark blue filled sections indicate the extent of the rock mass which has been assigned plastic properties. The blue material is able to deform plastically while the material outside the blue zone is an elastic medium only. The yellow-filled zones are the backfilled stopes; these zones do not appear in the strain plots. The backfill material can undergo elastic or plastic behaviour. Any red zone in a Figure defines an area which has been excavated with specified support pressures; these red areas are plotted as open stopes in the strain plots.

With this model, the crown pillar undergoes a progressive failure from a thickness of 140 feet to 80 feet. A series of Failure Zone Plots have been made to demonstrate the progressive failure: Figure 6-30 (140 foot crown pillar), Figure 6-31 (120 foot crown pillar), and Figure 6-32 (100 foot crown pillar). The total extent of failure in the 80 foot crown pillar is shown in Figure 6-33, Failure Zone Plot. It is interesting to note that the region of failure in the back of the lower level stoping (above 6700 level) is consistent with the area of damage observed as a result of rock burst 927 (October 1987).

The increase in plastic strain magnitudes have been plotted for each stage in crown pillar extraction. As stated above, the backfilled zones are not defined in the strain plots and any excavation with internal support pressures are plotted as open stopes.

The series of strain plots are shown: Figure 6-34 (140 ft. crown), Figure 6-35 (120 ft. crown), Figure 6-36 (100 ft. crown), and Figure 6-37 (80 ft. crown).

It can be seen from these plots that the largest increase in strain magnitude occurs with a reduction of crown pillar thickness from 120 feet to 100 feet, between Figure 6-36 and Figure 6-37.

The associated σ_1 and σ_2 plots for the last stage in the mining sequence (80 foot crown pillar) have been included. Figure 6-38 represents the Sigma 1 Plot and Figure 6-39 represents the Sigma 2 Plot.

Tensile failure is limited to the footwall zone of the 6700-6800 ore block as indicated by the tension region of the Sigma 2 plot. This tensile failure is also illustrated with the negative strain magnitudes in the strain plot, Figure 6-37.

The lack of failure beneath the 6400-6600 ore block was not indicative of the underground nor seismic observations. Prior to the mining of the destress slot and prior to failure of the crown pillar, a seismic study was carried-out for the 6600-6700 area. This survey indicated that an arc-shaped zone beneath the 6600 level was consistently devoid of any significant seismic events.

The lack of seismicity within this zone has led to the assumption that the rock mass had already failed prior to any mining above 6700 level. This 2D numerical modelling does not predict a failure envelop beneath 6600 level at any time in the mining history.

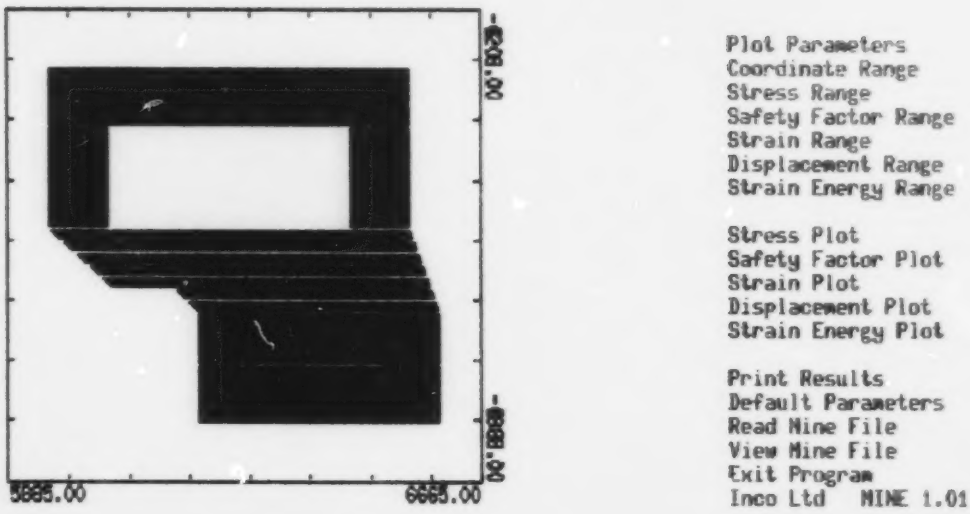

Figure 6-26 THE MINE2D MODEL INDICATING:
THE MINED, FILLED & INTACT AREAS.

- Model Run #7. MINE2D Plastic.
- No Backfill.
- Support Pressures: V=1000 psi & H=500 psi
- Crown Pillar Thickness is 140 feet.

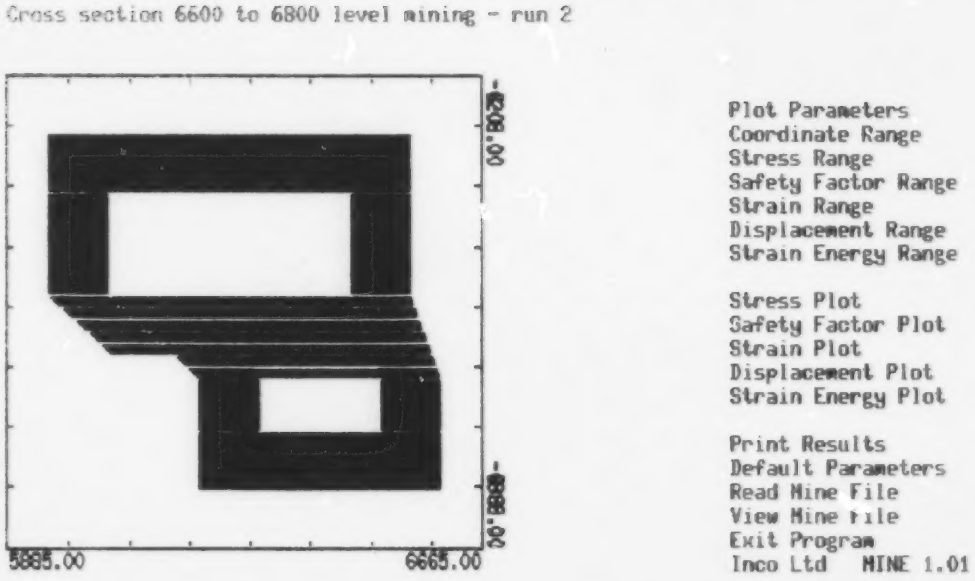

Figure 6-27 THE MINE2D MODEL INDICATING:
THE MINED, FILLED & INTACT AREAS.

- Model Run #7. MINE2D Plastic.
- No Backfill.
- Support Pressures: V=1000 psi & H=500 psi
- Crown Pillar Thickness is 120 feet.

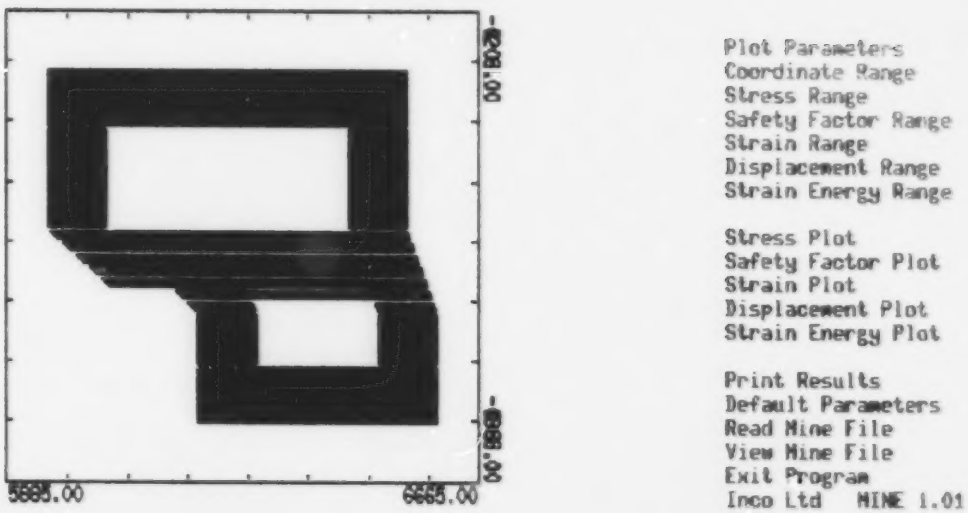

Figure 6-28 THE MINE2D MODEL INDICATING:
THE MINED, FILLED & INTACT AREAS.

- Model Run #7. MINE2D Plastic.
- No Backfill.
- Support Pressures: V=1000 psi & H=500 psi
- Crown Pillar Thickness is 100 feet.

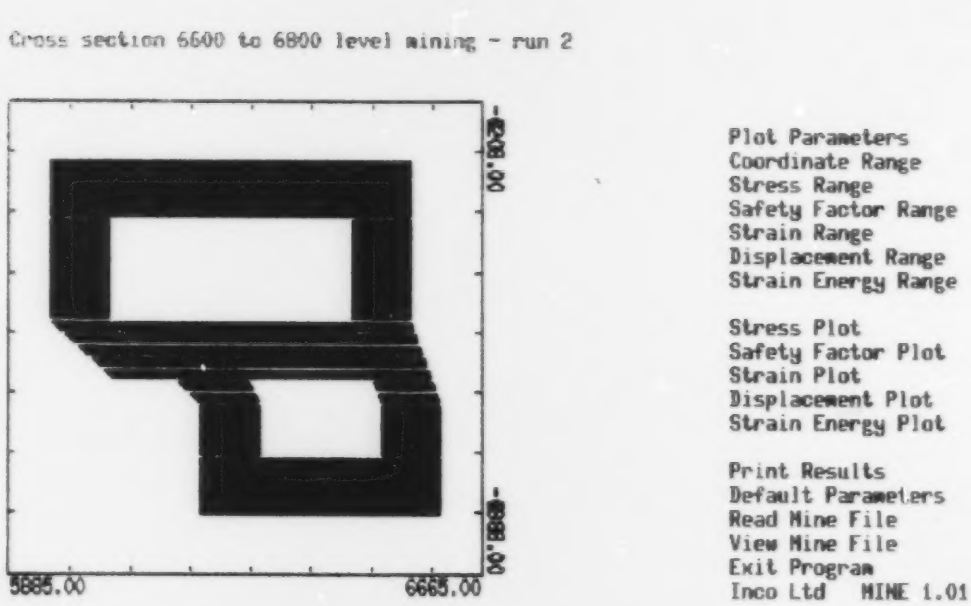

Figure 6-29 THE MINE2D MODEL INDICATING:
THE MINED, FILLED & INTACT AREAS

- Model Run #7. MINE2D Plastic.
- No Backfill.
- Support Pressures: V=1000 psi & H=500 psi
- Crown Pillar Thickness is 80 feet.

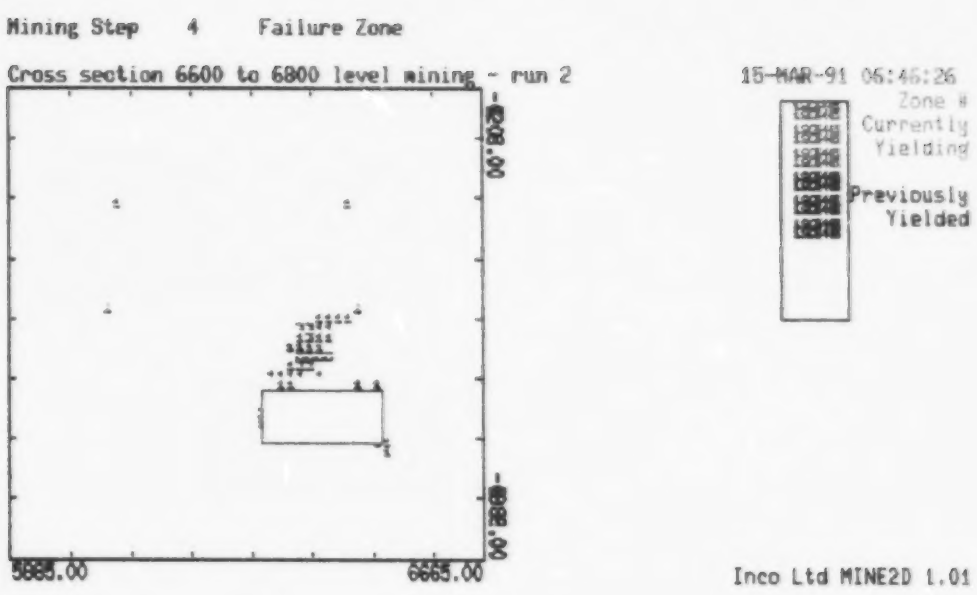

Figure 6-30 FAILURE ZONE PLOT.

- Model Run #7. MINE2D Plastic.
- No Backfill.
- Support Pressures: V=1000 psi & H=500 psi
- Crown Pillar Thickness is 140 feet.

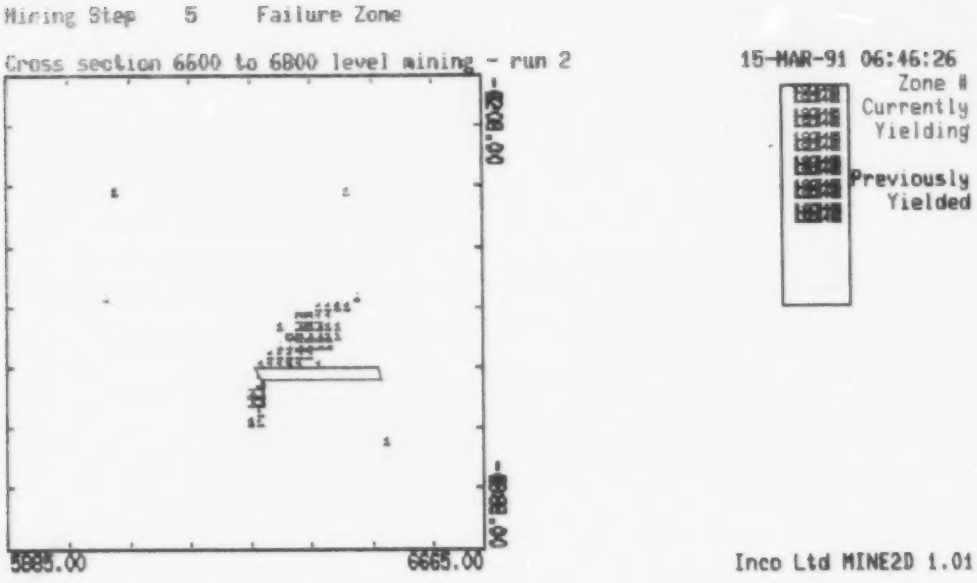

Figure 6-31 FAILURE ZONE PLOT.

- Model Run #7. MINE2D Plastic.
- No Backfill.
- Support Pressures: V=1000 psi & H=500 psi
- Crown Pillar Thickness is 120 feet.

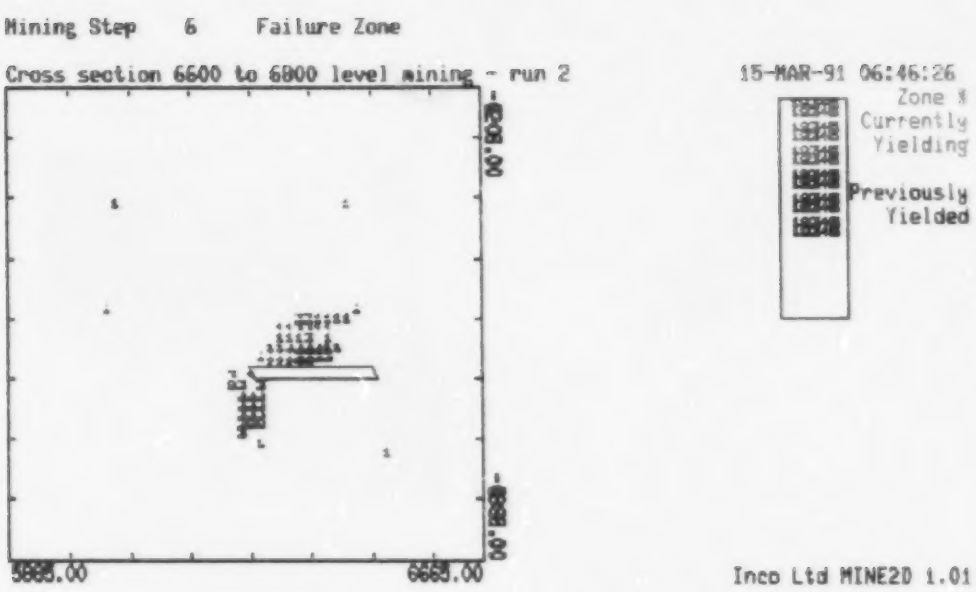

Figure 6-32 FAILURE ZONE PLOT.

- Model Run #7. MINE2D Plastic.
- No Backfill.
- Support Pressures: V=1000 psi & H=500 psi
- Crown Pillar Thickness is 100 feet.

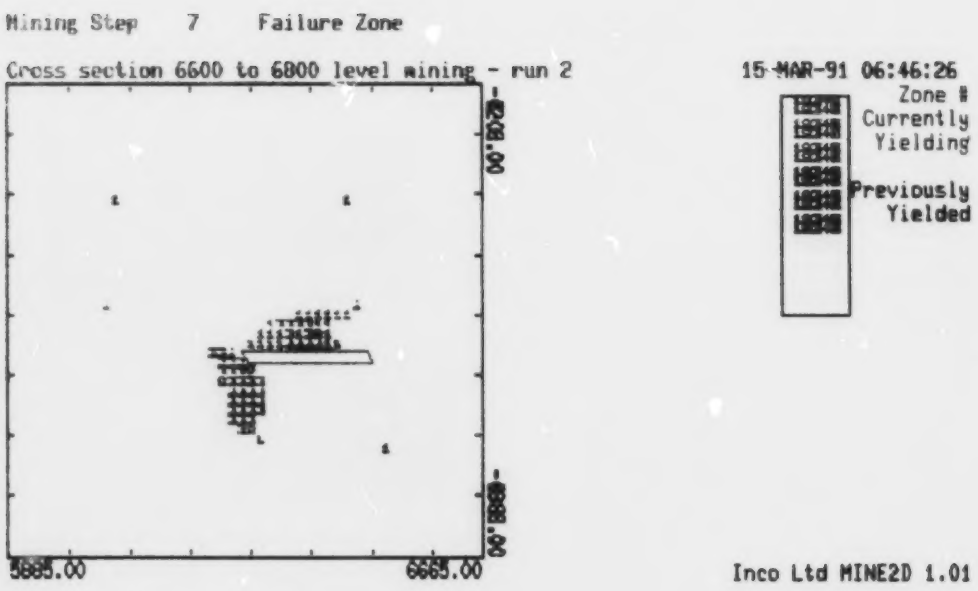

Figure 6-33 FAILURE ZONE PLOT.

- Model Run #7. MINE2D Plastic.
- No Backfill.
- Support Pressures: V=1000 & H=500 psi
- Crown Pillar Thickness is 80 feet.

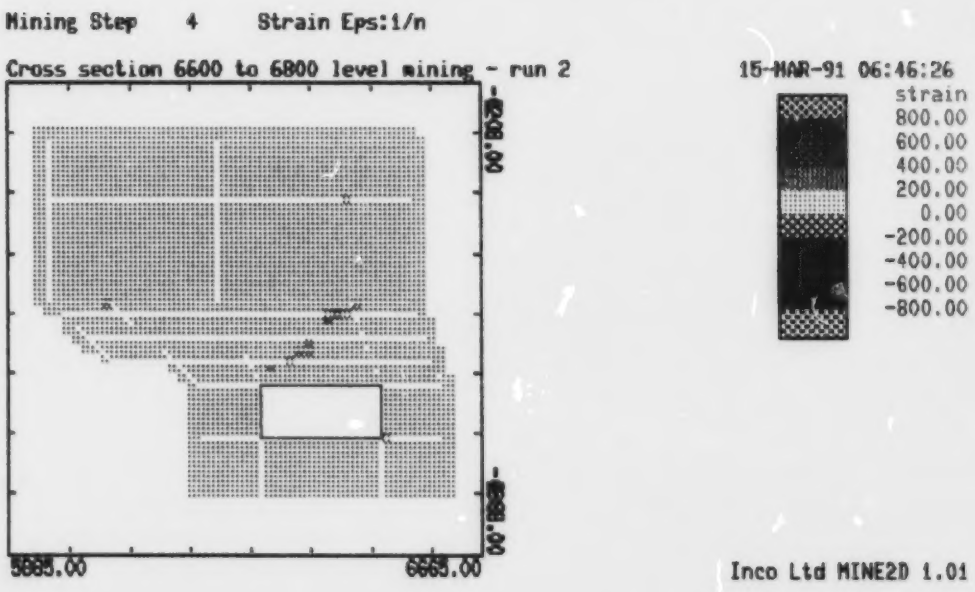

Figure 6-34 STRAIN PLOT.

- Model Run #7. MINE2D Plastic.
- No Backfill.
- Support Pressures: V=1000 psi & H=500 psi
- Crown Pillar Thickness of 140 feet.

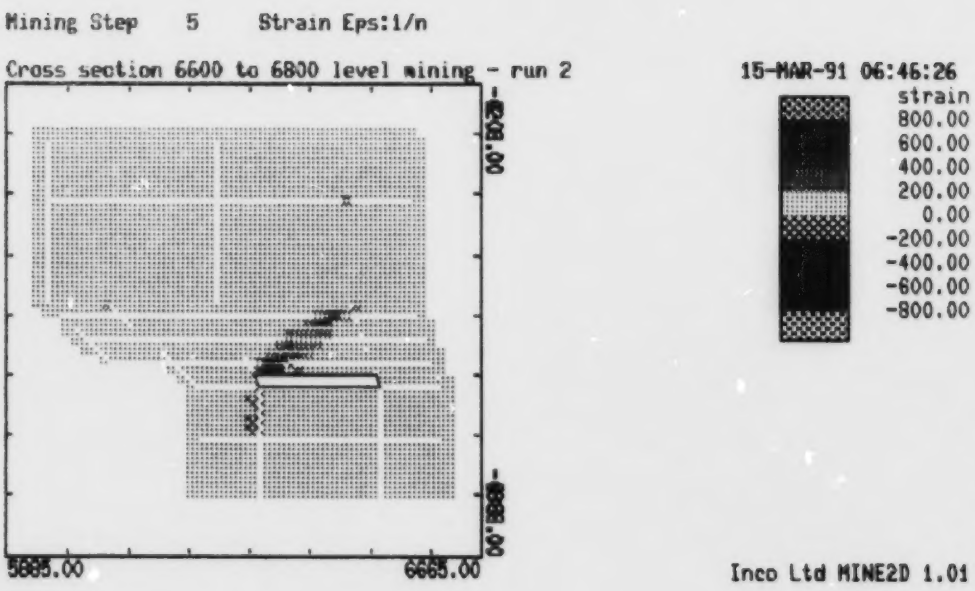

Figure 6-35 STRAIN PLOT.

- Model Run #7. MINE2D Plastic.
- No Backfill.
- Support Pressures: V=1000 psi & H=500 psi
- Crown Pillar Thickness is 120 feet.

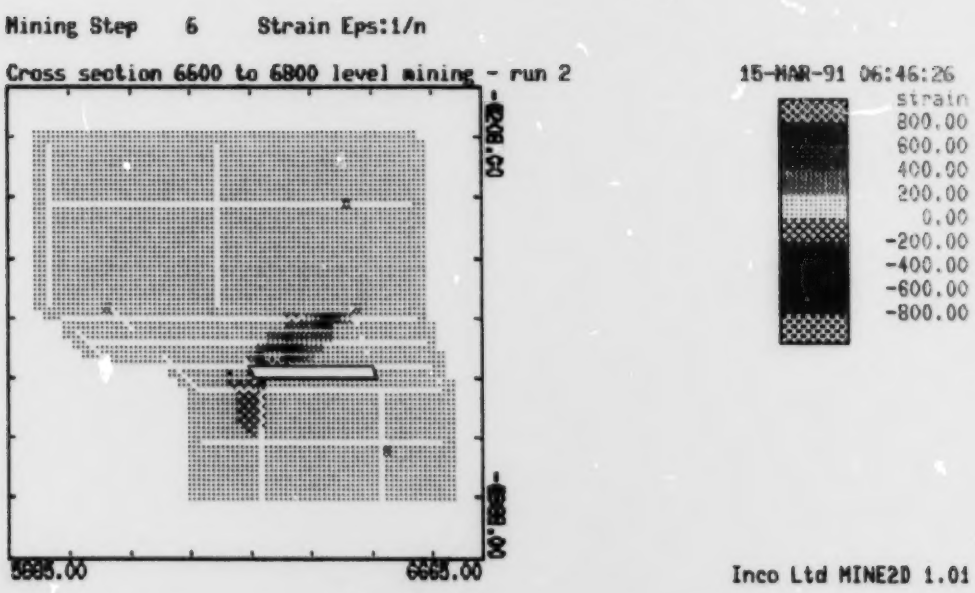

Figure 6-36 STRAIN PLOT.

- Model Run #7. MINE2D Plastic.
- No Backfill.
- Support Pressures: V=1000 psi & H=500 psi
- Crown Pillar Thickness is 100 feet.

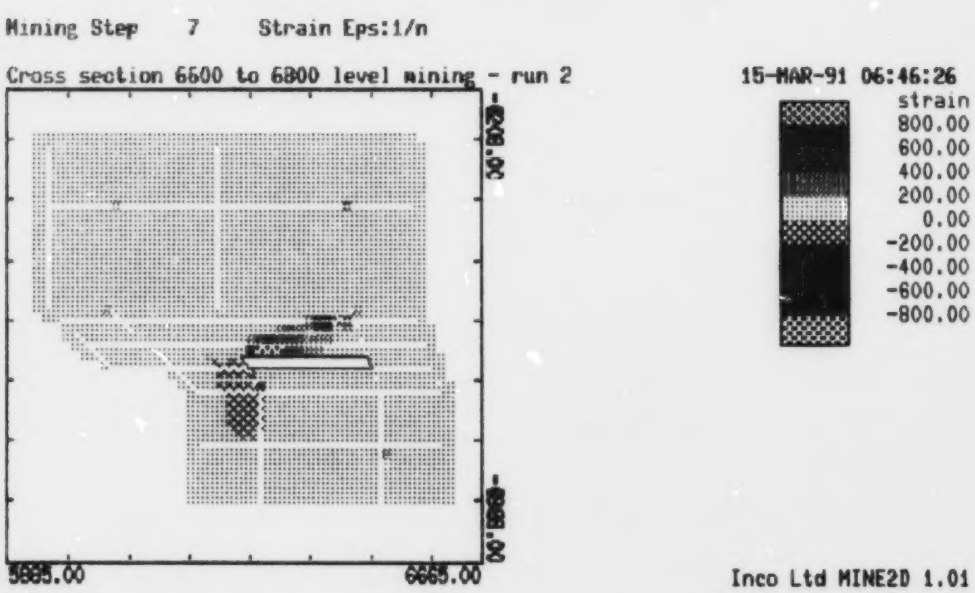

Figure 6-37 STRAIN PLOT.

- Model Run #7. MINE2D Plastic.
- No Backfill.
- Support Pressures: V=1000 psi & H=500 psi
- Crown Pillar Thickness is 80 feet.

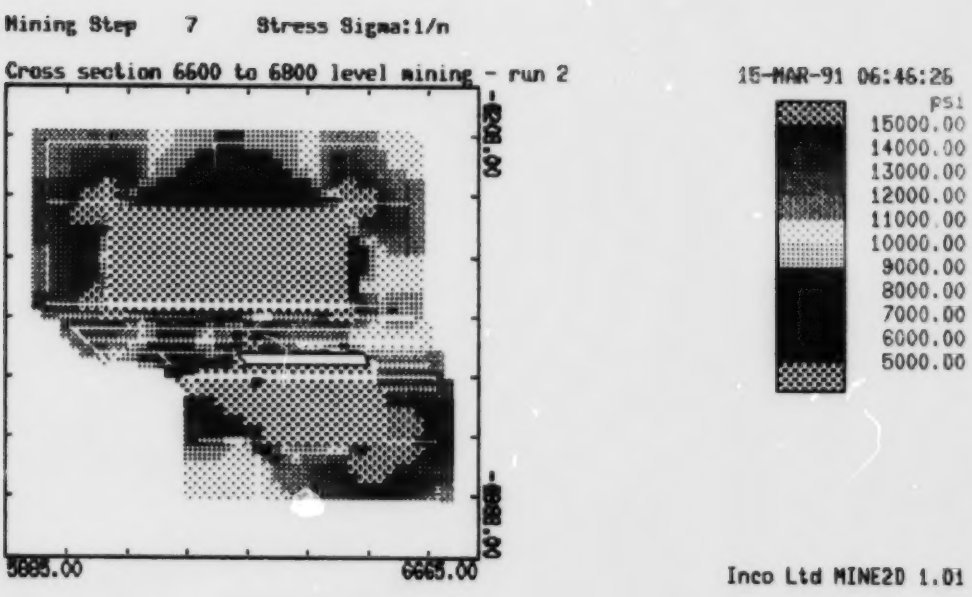

Figure 6-38 SIGMA 1: STRESS CONTOUR PLOT.

- Model Run #7. MINE2D Plastic.
- No Backfill.
- Support Pressures: V=1000 & H=500 psi
- Crown Pillar Thickness is 80 feet.

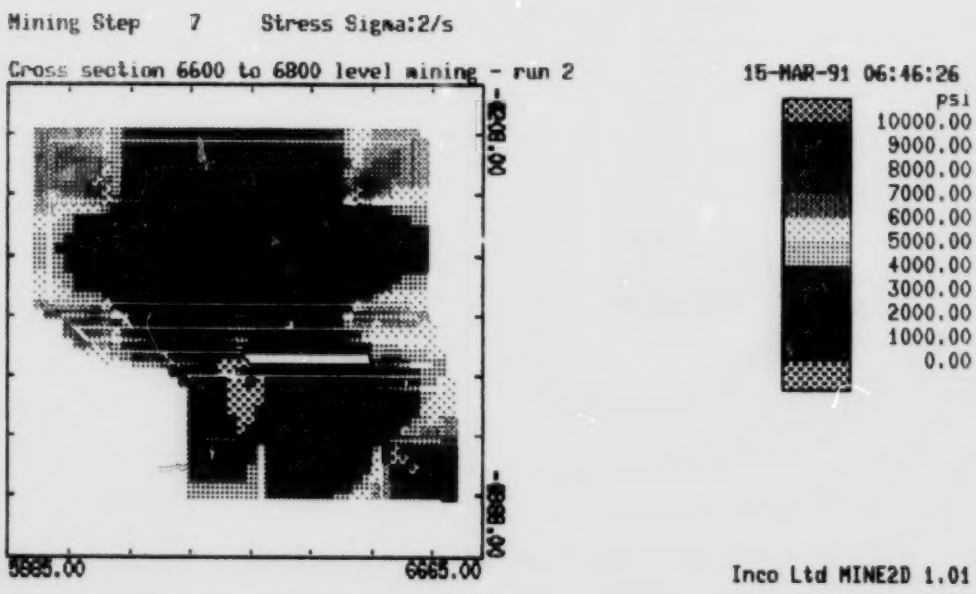

Figure 6-39 SIGMA 2: STRESS CONTOUR PLOT.

- Model Run #7. MINE2D Plastic.
- No Backfill.
- Support Pressures: V=1000 & H=500 psi
- Crown Pillar Thickness is 80 feet.

6.4.8 Model Run #8: Plastic, Boundary Element Modelling, MINE2D

In order to attempt a duplication of the assumed failure zone beneath 6600 level, a third MINE2D plasticity model was run using altered input parameters.

The ore zone strength properties were reduced to one-half of the value used in the previous modelling runs. This strength for the ore was reduced to 6000 psi, as opposed to the 12000 psi used in the first two MINE2D plastic runs. The mining was limited to the 6400-6600 ore block with the support pressures equal to 1000 psi in the vertical direction and 500 psi in the horizontal sense.

The geometry of the model is shown in Figure 6-40. This plot indicates the point in the mining sequence where the upper ore block from 6400 level to 6600 level has been mined. No other mining has been simulated with this model. The dark blue filled areas in Figure 6-40 correspond to the intact rock mass which is able to deform plastically. The red filled area is the 6400-6600 region which has been excavated and where support pressures have been applied to the walls.

The results of this model did not indicate any region of failure beneath 6600 level. The model did, however, indicate some additional failure in the hangingwall and footwall of the upper ore block excavation. There is still no general failure envelop.

The Failure Zone associated with the excavation of the upper ore block is plotted in Figure 6-41. The lack of symmetry in the failure patterns is due to the different strengths and elastic properties of the three materials within the model.

One final MINE2D plastic analysis was carried-out; this model is detailed in the following section 6.3.3.9. The model was used to examine the effect of reducing the support pressures within the excavations. The set-up of the Model Run #9 is identical to this Model Run #8, therefore the reduced ore strength was also used in the following model.

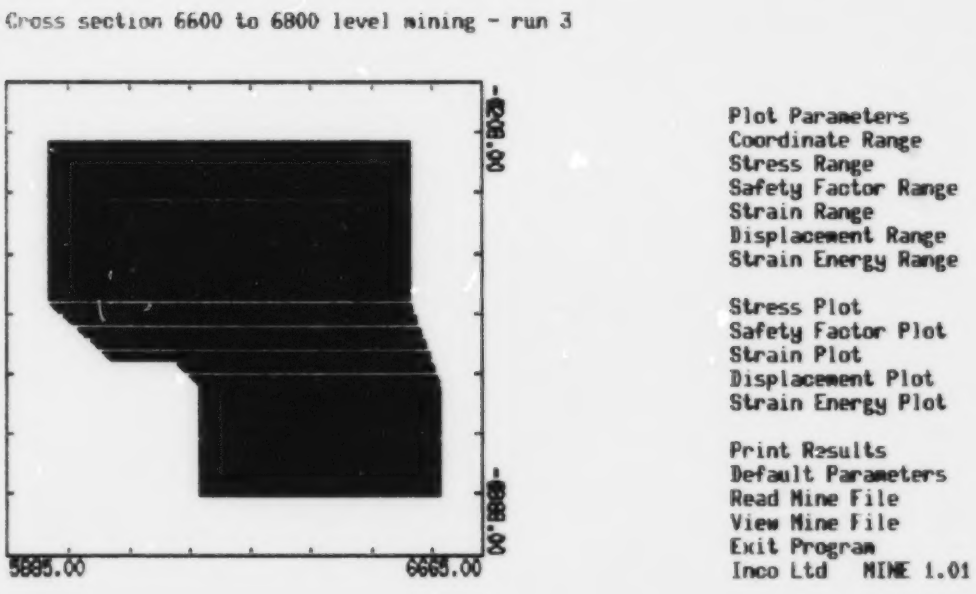

Figure 6-40 THE MINE2D MODEL INDICATING:
THE MINED, FILLED & INTACT AREAS

- Model Run #8. MINE2D Plastic.
- No Backfill.
- Support Pressures: V=1000 psi & H=500 psi
- Strength of the Ore is Reduced to 6000 psi
- Mining of 6400-6600 Ore Block Only.

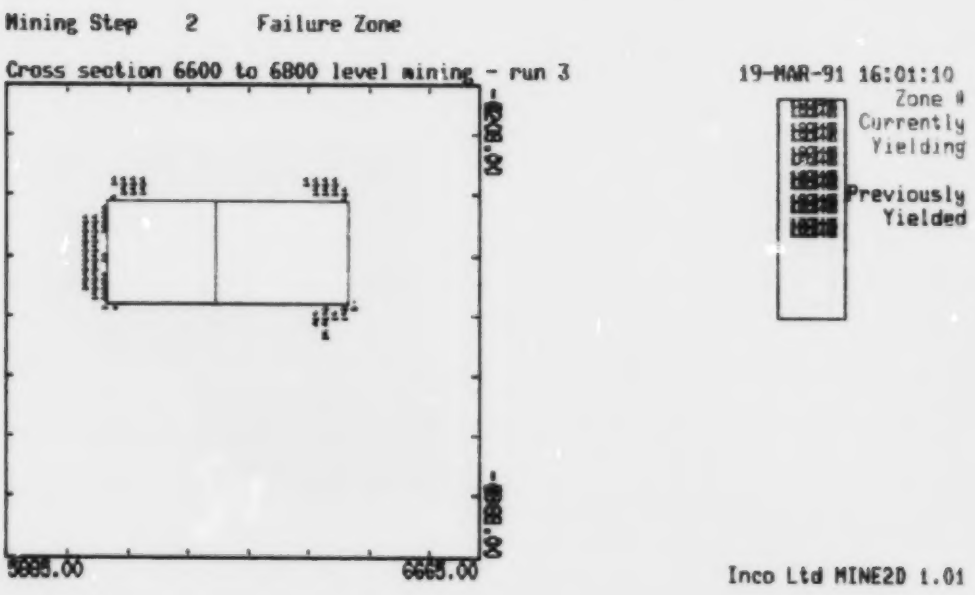

Figure 6-41 FAILURE ZONE PLOT.

- Model Run #8. MINE2D Plastic.
- No Backfill.
- Support Pressures: V=1000 psi & H=500 psi
- Strength of the Ore is Reduced to 6000 psi
- Mining of 6400-6600 Ore Block Only.

6.4.9 Model Run #9: Plastic, Boundary Element Modelling, MINE2D

A final plastic, boundary element model of the 6400 to 6800 level cross-section was run. This model was used to determine the effect of the internal backfill pressures.

An identical input data file as the previous model (Run #8) was used, again employing the reduced 6000 psi ore strength. However, the difference with this model is with the backfill pressures. The data file was altered to include reduced pressures within the backfill material. The pressures were reduced from 1000 psi (vertically) and 500 psi (horizontally) to 50 psi in both the horizontal and vertical directions.

The Failure Zone Plot is represented in Figure 6-42. In this plot, a failure envelop has finally developed beneath the 6600 level. This failure zone is non-symmetrical due to the different material properties used in the model.

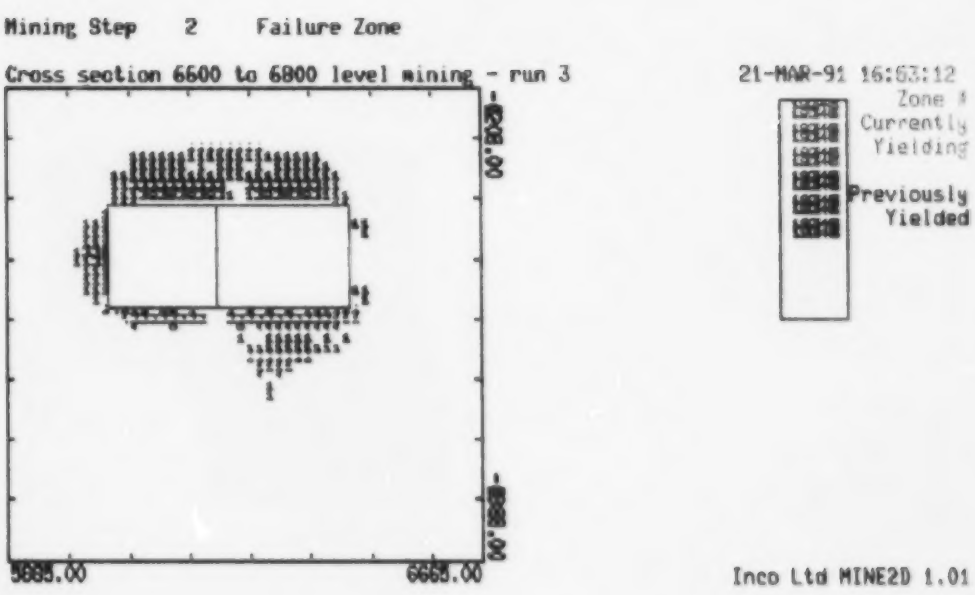

Figure 6-42 FAILURE ZONE PLOT.

- Model Run #9. MINE2D Plastic.
- No Backfill.
- Reduced Support Pressures: V=50 psi, H=50 psi
- Strength of the Ore is Reduced to 6000 psi
- Mining of the 6400-6600 Ore Block Only.

6.5 Summary of the MINE2D Modelling

From an analysis of the modelling runs, the following results of the MINE2D calibration modelling indicate a reasonable consistency with the observed rock mass behaviour: (i) the nature of the failure of the crown pillar along a diagonal shear, (ii) the thickness of the crown at which failure occurred, and, (iii) the probable damage area in the 6700-6800 ore block vicinity.

On the other hand, the progressive nature of the failure in the model, as the crown pillar thickness was reduced from 140 feet to 80 feet, is not consistent with the observed ground behaviour.

The previous observations of the rock mass indicated that the crown pillar failed rapidly and violently. In fact, it was believed that the failure of the crown pillar coincided with a large rock burst in October 1987 when the crown was 90 feet thick. Also of an inconsistent nature, with regard to the modelling predictions, is the high levels of stress associated with a crown pillar that is 80 feet thick.

The nature of the modelled failure indicates that the behaviour of the overall geometry is stiff relative to the pillar stiffness. This accounts for the predicted *progressive* failure with the MINE2D modelling as opposed to the observed *sudden* failure. In actuality, the violent nature of the observed failure indicates that the overall mining geometry was soft relative to the stiffness of the crown pillar.

This leads to another aspect of the 2D model which has a large impact on the results: the modelled geometry. The extent of the mining above 6600 level, within the cross-sectional model, is not at all representative of the actual mining conditions. In reality, the mining above 6600 level is effectively continuous to well above 6000 level. The height of the upper ore block should be in excess of 600 feet rather than the 170 feet represented in the cross-section model.

If the upper country mining had been included in the model, the shape of the upper ore block would be rectangular, with a much larger vertical height versus horizontal width. The effect of a longer upper ore block shape would have significantly influenced stresses in the crown pillar below 6600 level. This increase in height in the upper ore block would have also aided in making the model "softer", to more accurately simulate the failure of the pillar.

Also of importance to the modelling results is the input parameters. It was demonstrated that a reduction in the strength of the ore material had very little effect on development of the failure zone.

In fact, the reduction in ore strength served to increase the failure zone only in the footwall region of the 6400-6600 ore block.

On the other hand, the development of a failure envelop beneath the 6600 level was extremely sensitive to the support pressures provided by the yielding rib pillars and backfill. These values have not been confidently determined. For the most part, there is no database from which a set of defined values for the rib pillar and backfill combination could be obtained. This is obviously a much needed set of input properties since the numerical modelling results are heavily influenced by these values.

As a precursor to any 3D modelling, a set of 2D models should be carried-out whereby the effect of the rib pillar/backfill combination should be more carefully studied. The 2D modelling should be set up to develop realistic limits for support pressures and load responses in mechanised cut-and-fill stopes. The models should incorporate the fact that the vertical direction of the pillars were continuous while the horizontal direction had been bisected with a slot.

In summary, the fact that the modelling results appear to be realistic may be due to a fortuitous combination of selected support pressures with an incomplete modelling geometry for the mining above 6600 level. There is a strong possibility that the resulting input parameters obtained from the MINE2D modelling, when applied to a MINE3D plasticity code, would give erroneous results for the same mining region.

7.0 3D PLASTICITY MODELLING

The numerical modelling code, MINE3D, is a research program which was developed as part of a COMDA contract. This is a three-dimensional, plastic, boundary element code which has been developed specifically for this project. The formulation of MINE3D is given in Volume 2, and the user's manual is given in Volume 5.

7.1 MINE3D

The MINE3D program is a three-dimensional boundary element code which has two distinct features: (1) it simulates localized regions of plastic yield within an elastic continuum; and (2) multiple regions containing different materials can be defined to simulate backfill within ore bodies.

This section of the numerical calibration report discusses the capabilities of MINE3D for the simulation of the rock mass response to mining at the monitoring site at Creighton Mine. This evaluation also includes model simulations using 3DEC runs in parallel with the MINE3D simulations. The 3DEC model provides both an independent analysis for comparison to MINE3D and also a basis for estimating the extent of the plastic failure region in order to define the required number of volume elements in the MINE3D analysis. The evaluation plan involved a series of calculations similar to those performed with BEM3D and FLAC for the different mining stages. Table 7-1 outlines the mining sequence used to simulate the actual sequence.

Step	
1	Pre-Destress Slot Mining --- Ore above 6600 level and below 6800 level has been mined. An approximately 40-meter thick crown pillar remains.
2	Destress Slot Mining --- The slot, approximately 7 m (23 ft) wide by 83 m (272 ft) long by 53 m (474 ft) high, has been mined in the crown pillar.
3	Mining of VRM Panel #1
4	Mining of VRM Panel #2
5	Mining of VRM Panel #3
6	Mining of VRM Panel #4
7	Mining of VRM Panel #5
8	Mining of VRM Panel #6

Table 7-1 Mining Sequence used in the Numerical Modelling

The VRM panel mining sequence outlined in Table 7-1 (steps 3 through 8) corresponds to that given for the FLAC modelling, in Table 5-9 (steps 6 to 11) and in Figure 5-9.

7.2 Input Parameters for Case Study Site

The rock mass deformation and strength properties used for this 3D modelling study were based upon the input values derived from the BEM3D and FLAC analyses.

The rock mass elastic properties, Table 7-2, were assumed

Young's modulus	E = 68 GPa ($1x10^7$ psi)
Poisson's ratio	ν = 0.25

Table 7-2 Case Study Modelling : Elastic Properties

The assumed rock mass strength parameters, Table 7-3, were used.

Rock Mass	
Unconfined Strength	C_o = 85 MPa (12,500 psi)
Tensile Strength	T_o = 0 MPa
Cohesion	coh = 22 MPa (3,200 psi)
Dilation Angle	dil = 0°
Internal Friction Angle	ϕ = 35°

Table 7-3 Case Study Modelling: Rock Mass Strength Parameters

The in-situ stress regime at the 6650 level was assumed for the far-field stress condition in this study, Table 7-4. The far-field stresses were assumed to be hydrostatic.

σ_1 = 93.5 MPa (13,560 psi)	0°\90° (dip\azimuth)
σ_2 = 60.0 MPa (8,700 psi)	0°\180° (dip\azimuth)
σ_3 = 60.0 MPa (8,700 psi)	vertical

Table 7-4 In-Situ Stress Regime Used in the Modelling

7.3 MINE3D Model Preparation

An idealized model of the monitoring site was created first with MINE3D in order to provide a verification test for comparison to 3DEC, and also to evaluate the limitations of MINE3D for a problem of this size. This analysis is also described in Volume 2: Mathematical Formulation and Code Development.

The MINE3D model dimensions approximated the conditions at the 6600-6700 level ore block at Creighton Mine. The slot width in the model is 6.1 m (20 ft), the length is 73.2 m (240 ft), and the height is 42.7 m (140 ft). The mined ore blocks above and below the crown pillar are modelled as two rectangular polyhedra with dimensions 182.9 m (600 ft) by 73.2 m (240 ft) by 30.5 m (100 ft). Figure 7-1 presents the MINE3D model.

The model is defined within a parallelepiped grid consisting of (31x13x18) nodes. The node spacing is 6.1 m (20 ft) in the i-, j- and k- directions. This model contains 2,434 surface elements and 2,440 surface nodes. The size of the parallelepiped grid was the minimum size sufficient to encompass the mining region. This model requires approximately 75 Mbytes for storage of the nodal coefficients.

As indicated in Figure 7-1, the slot does not extend completely from the lower mining block to the upper block. A continuous slot would require the use of re-entrant corner nodes in the model. Re-entrant corners pose a particular problem in boundary elements because the fictitious point force solution is infinite at such corners.

Corner offsets, as discussed in Section 4.3.3 of Vol. 2, can be used to move the corner calculation so that this effect is minimized. The optimum corner offset for re-entrant corners has not been studied at present. For this calculation, because of the excessive solution time required, re-entrant corners were eliminated from the model, to avoid the problem completely, by leaving a 6 m space between the slot and the upper and lower blocks. The consequence of leaving this gap was studied with the 3DEC model.

The MINE3D model was run as an elastic analysis for the second mining stage (i.e., ore above the 6600 level and below the 6800 level mined and the destress slot mined). Unfortunately, the solution time for this model was over seven days on the SUN SPARCStation 2 computer. The run time is primarily influenced by the time required for access of virtual memory to store and retrieve the coefficients. (This problem is discussed in Section 4.10 of Vol. 2, and the consequence for the calibration study is discussed below.)

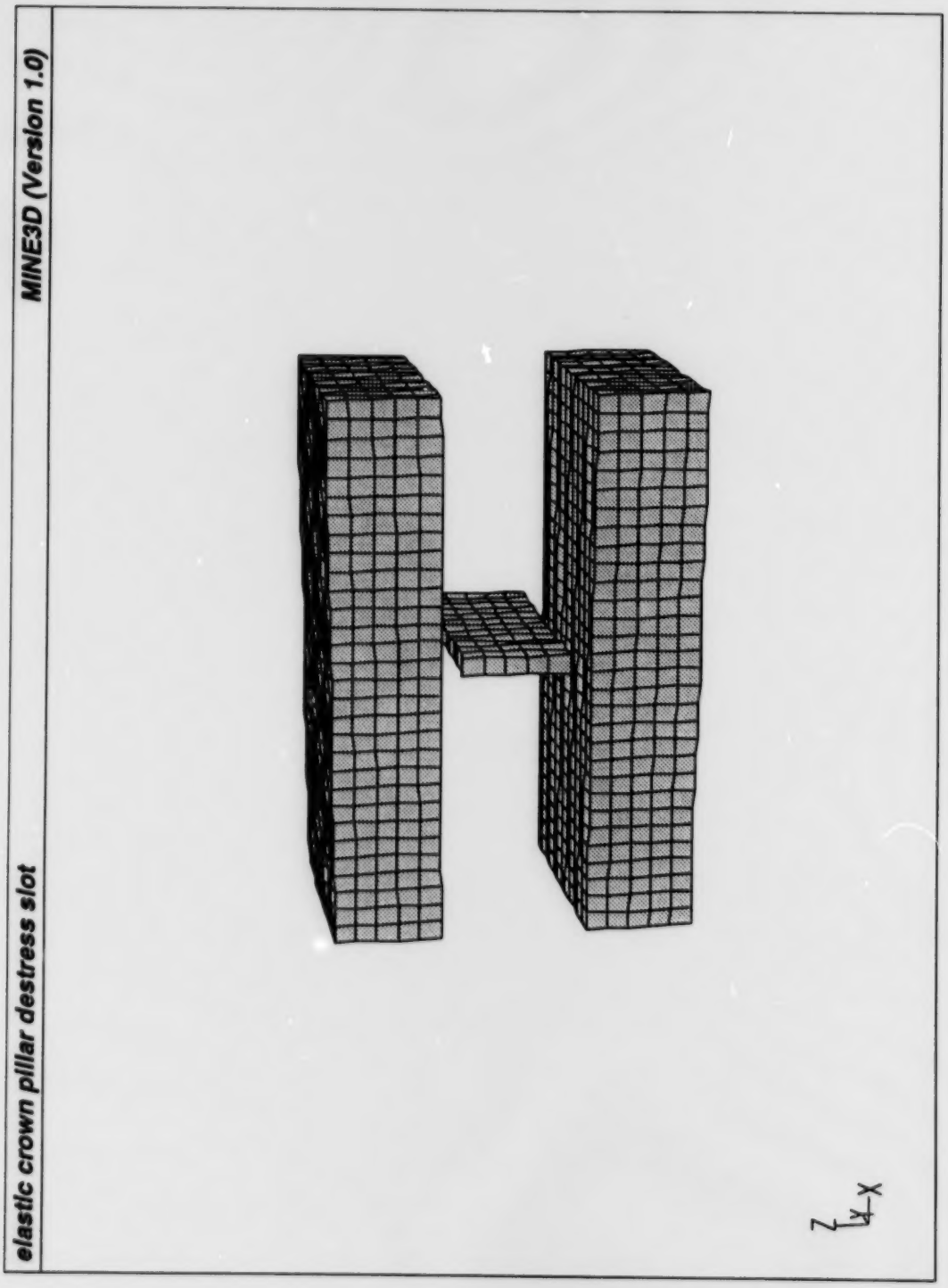

Figure 7-1 MINE3D Model of Destress Slot in Large Crown Pillar

7.4 3DEC Model Preparation

A 3DEC model was created using the same model dimensions as that for the MINE3D numerical model. The 3DEC modelling geometry is shown in Figures 7-2(a,b). Figure 7-2(a) shows the outer boundary of the 3DEC model, which has dimensions of 600 m by 600 m by 600 m. The model is subdivided into 15 joined blocks (i.e., blocks are "glued" together). The inner three blocks represent the mined region, as shown in Figure 7-2(b). Compare this Figure 7-2(b) to Figure 7-1. The blocks in the 3DEC model are subdivided into 24,000 finite difference tetrahedral zones. Figure 7-3 shows a close-up view of the zoning in the crown pillar region (the surrounding blocks are hidden for better viewing). A second 3DEC model was also created with the slot extending completely from the lower mining block to the upper block.

The 3DEC simulation was also performed as an elastic analysis of mining stage 2 for direct comparison to MINE3D. The calculation was conducted on an 80836 microcomputer, and the solution time was approximately eight hours.

Figure 7-2(a) Model Boundary:
3DEC Model of Destress Slot in Large Crown Pillar

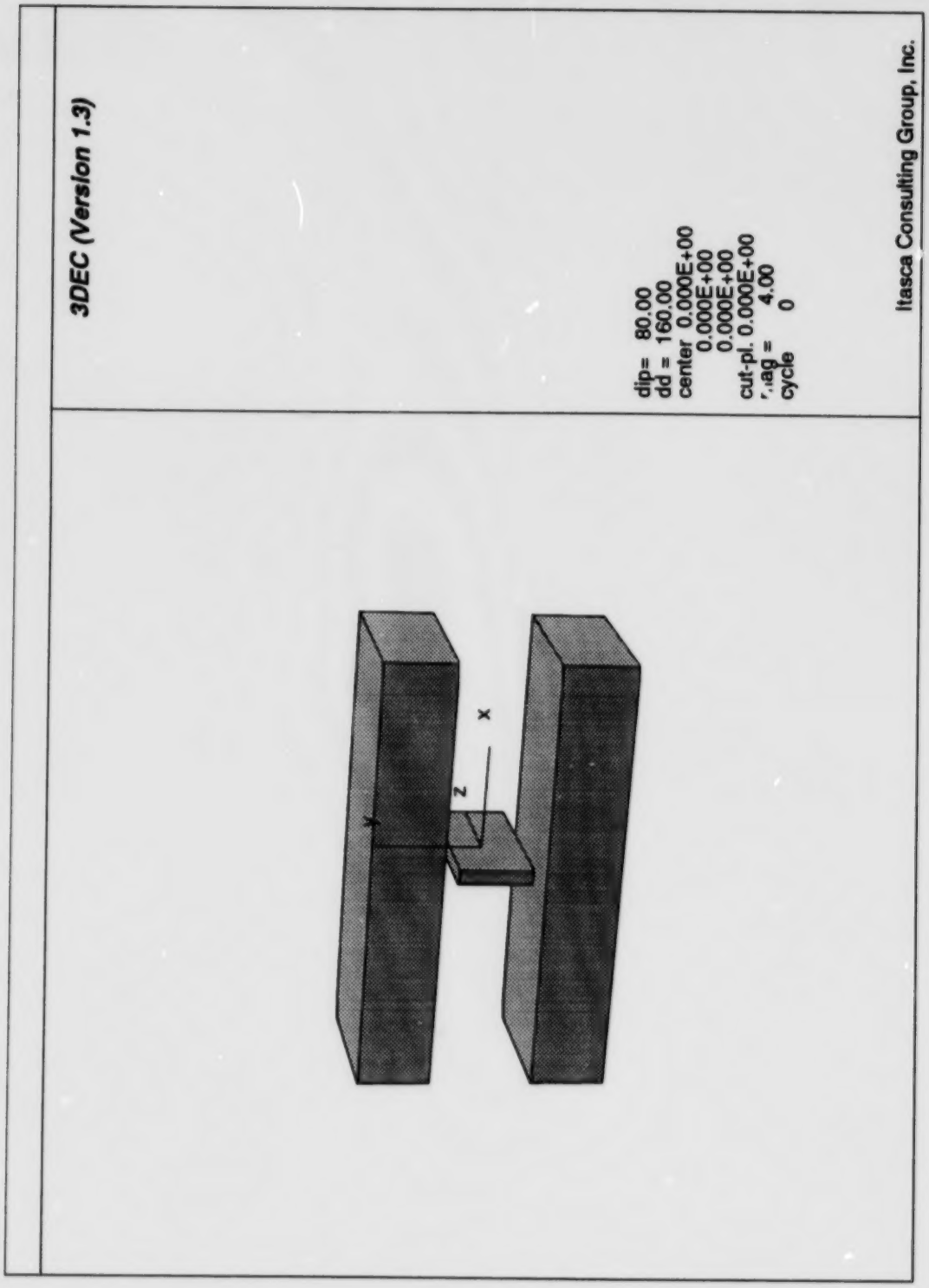

Figure 7-2(b) Destress Slot and Upper and Lower Mining Blocks: 3DEC Model of Destress Slot in Large Crown Pillar

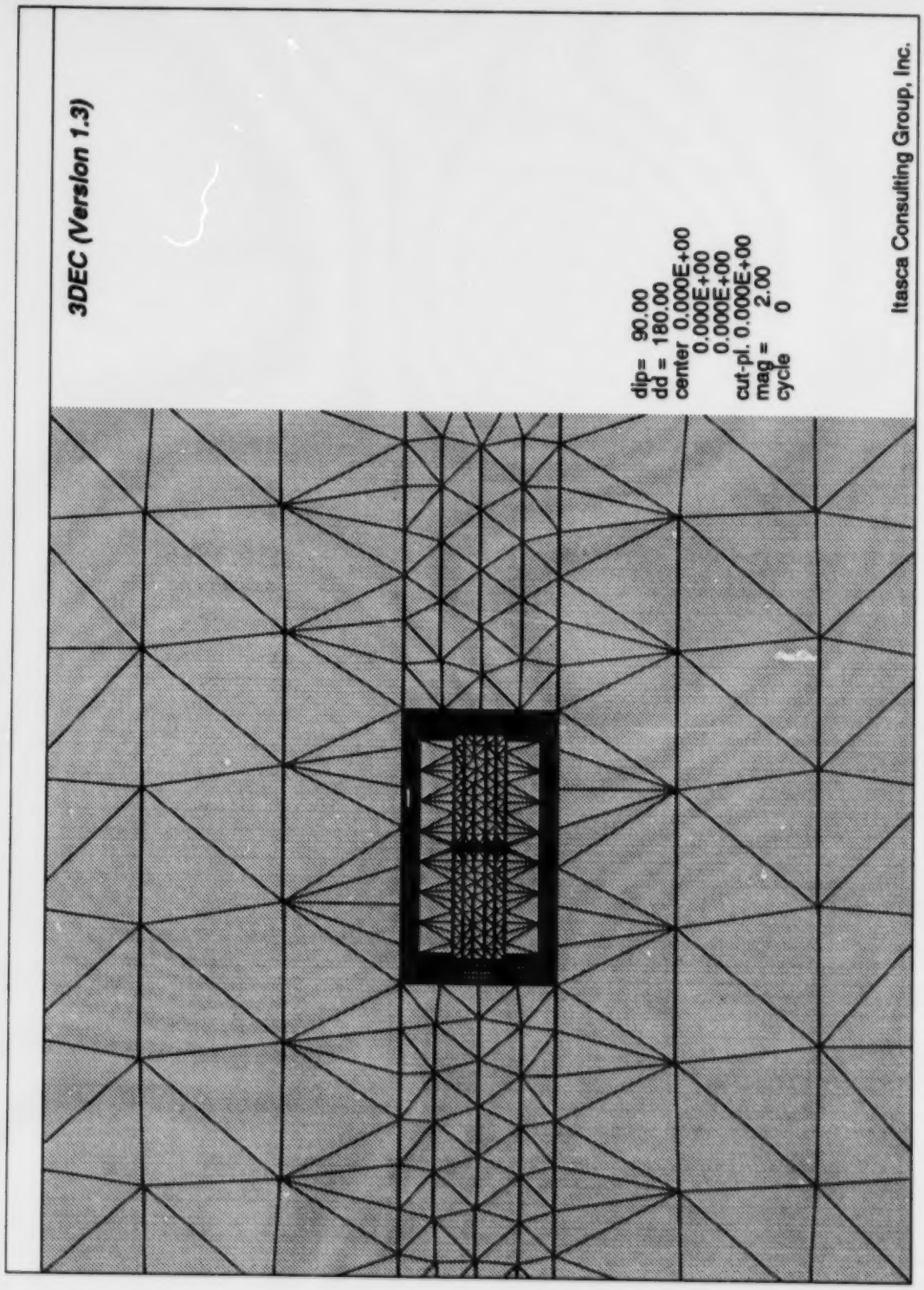

Figure 7-3 Close-Up of Crown Pillar Region Showing 3DEC Model Zoning on Vertical Plane Through Centre of Model

7.5 Comparison Between MINE3D and 3DEC, Elastic Analysis

The results of the two models are compared in Figure 7-4 through to Figure 7-7. Figure 7-4(a,b) shows the comparison of the displacement vectors along a horizontal plane for MINE3D and 3DEC. The predicted displacement vectors along a vertical plane are also compared, Figure 7-5(a,b), for MINE3D and 3DEC respectively.

The directions of the displacements, on both the vertical and the horizontal planes, compare almost exactly for the two models; however, the displacement magnitudes are not as closely matched. The maximum displacement vector on the horizontal plane through the destress slot predicted by MINE3D is approximately 5% higher (0.0396 vs 0.0374) than that predicted by the 3DEC model. The displacements on the vertical plane differ more significantly; the MINE3D model predicts a maximum displacement which is approximately 35% higher (0.05677 vs 0.04195) than the 3DEC model prediction.

The discrepancy in displacement magnitudes is a result of the discretization of the MINE3D model in the vicinity of the destress slot. The discrepancy is higher in the vertical plane since the destress slot contains only one boundary element across its width. For the horizontal plane, the MINE3D and 3DEC magnitudes agree more closely since the maximum displacement is located along the slot wall; the slot wall contains several boundary elements in the MINE3D model.

As is the case with the FLAC code, MINE3D requires at least four elements across an opening to get a reasonable solution. However, if the destress slot is divided into four elements, the total model would require at least (4 x 31) x 13 x 18 = 29016 nodes, which would subsequently require approximately 700 mbytes for the coefficients and an infinitely long time to run.

Maximum principal stress contours from MINE3D are compared to principal stress tensor plots from 3DEC. Figure 7-6(a,b) shows the comparison for stresses along a horizontal plane through the destress slot, while Figure 7-7(a,b) exhibits the comparison of the stresses along a vertical plane through the destress slot.

In 3DEC, the principal stresses are plotted at the centroid of the triangle created by the intersection of the plotting plane with the tetrahedral zone. The stresses are plotted as projections of the three principal stress components on the plotting plane. Although the MINE3D and 3DEC plots are of different types, they both show the same form of stress redistribution around the slot and also calculate similar areas of stress concentrations. The values of peak stress do not compare closely, but this is more a function of the difference in stress calculation locations in the two models, i.e. the zoning is much finer in the 3DEC model at the slot corners, as compared to the MINE3D model which has only one boundary element across the destress slot width.

Since the stress concentrations are at the corners in the models, the MINE3D model will have the least accurate stress results with the one element width.

As far as the comparison between stress contours (MINE3D) and stress trajectories (3DEC) is concerned, this is a dilemma. 3DEC has difficulty with stress contours, and this is the reason for using the stress trajectories. Meanwhile, the MINE3D code only has the capability of displaying the stress contours. However, even if the MINE3D code was supplemented with the stress trajectory capabilities to more clearly see the difference with the stress redistributions, the difference between the calculated stresses can only be resolved with more elements. As was previously discussed, the requirement of additional boundary elements within the MINE3D model parallels a requirement for computer hardware which does not exist with present technology.

A final analysis using 3DEC with a continuous slot between the upper and lower mining blocks showed little difference between results for the non-continuous slot throughout the central portion of the slot. Stress concentrations do occur at the top and bottom of the slot, as shown in Figure 7-7(a,b). However, this does not appear to have a significant influence on stresses and displacements around the central region of the slot.

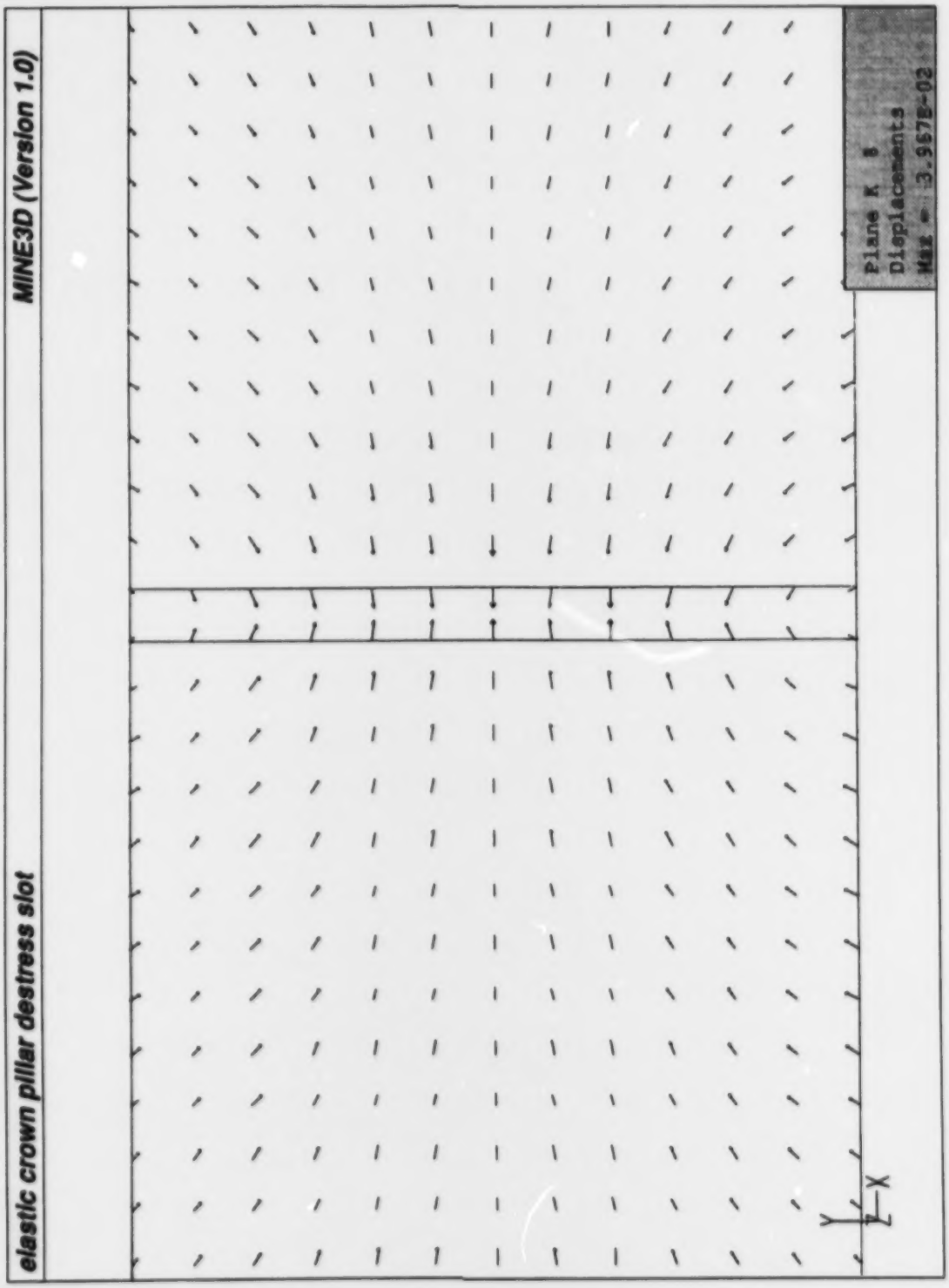

Figure 7-4(a) MINE3D Model:
Displacement Vectors on Horizontal Plane Through Destress Slot

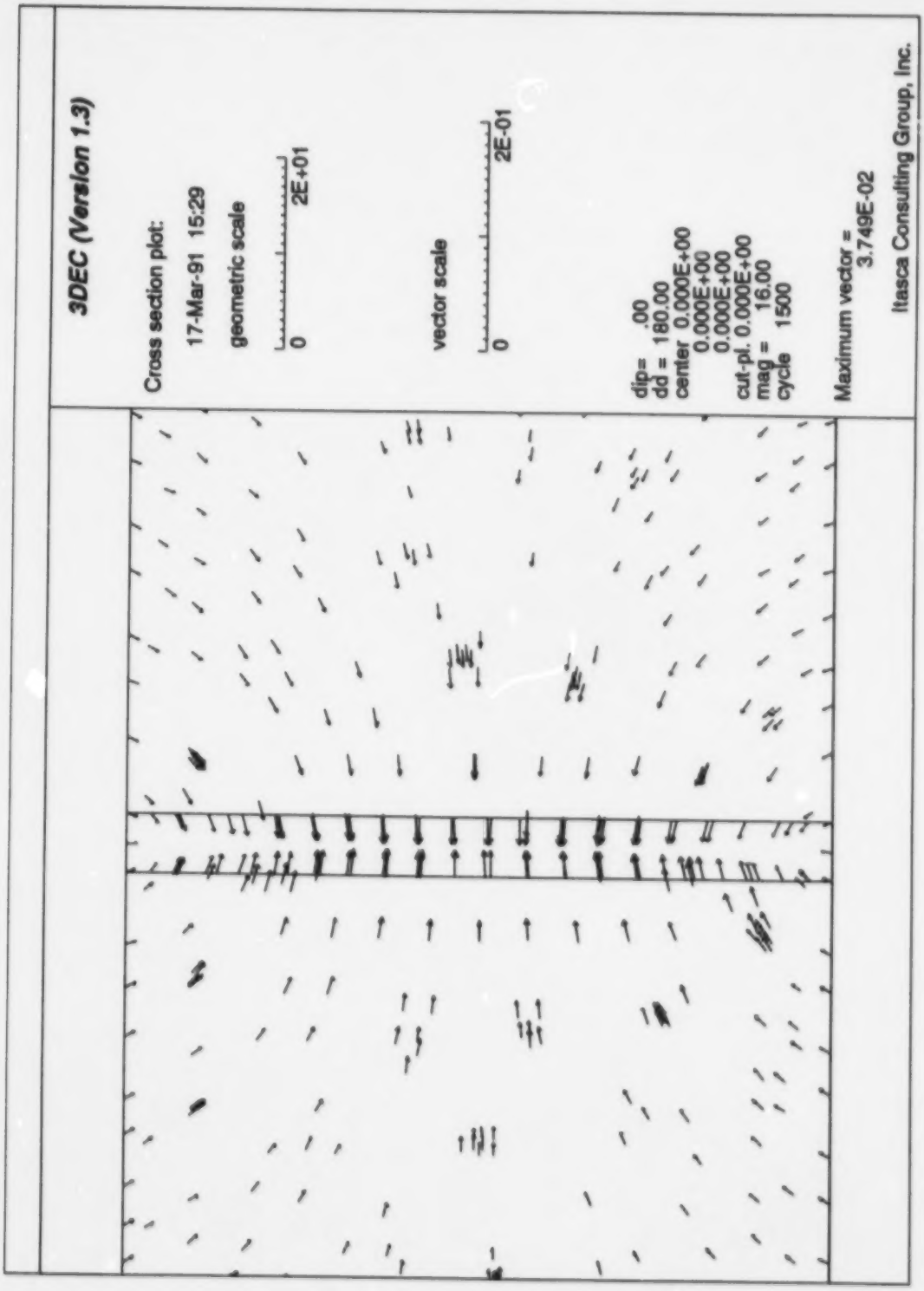

Figure 7-4(b) 3DEC Model:
Displacement Vectors on Horizontal Plane Through Destress Slot

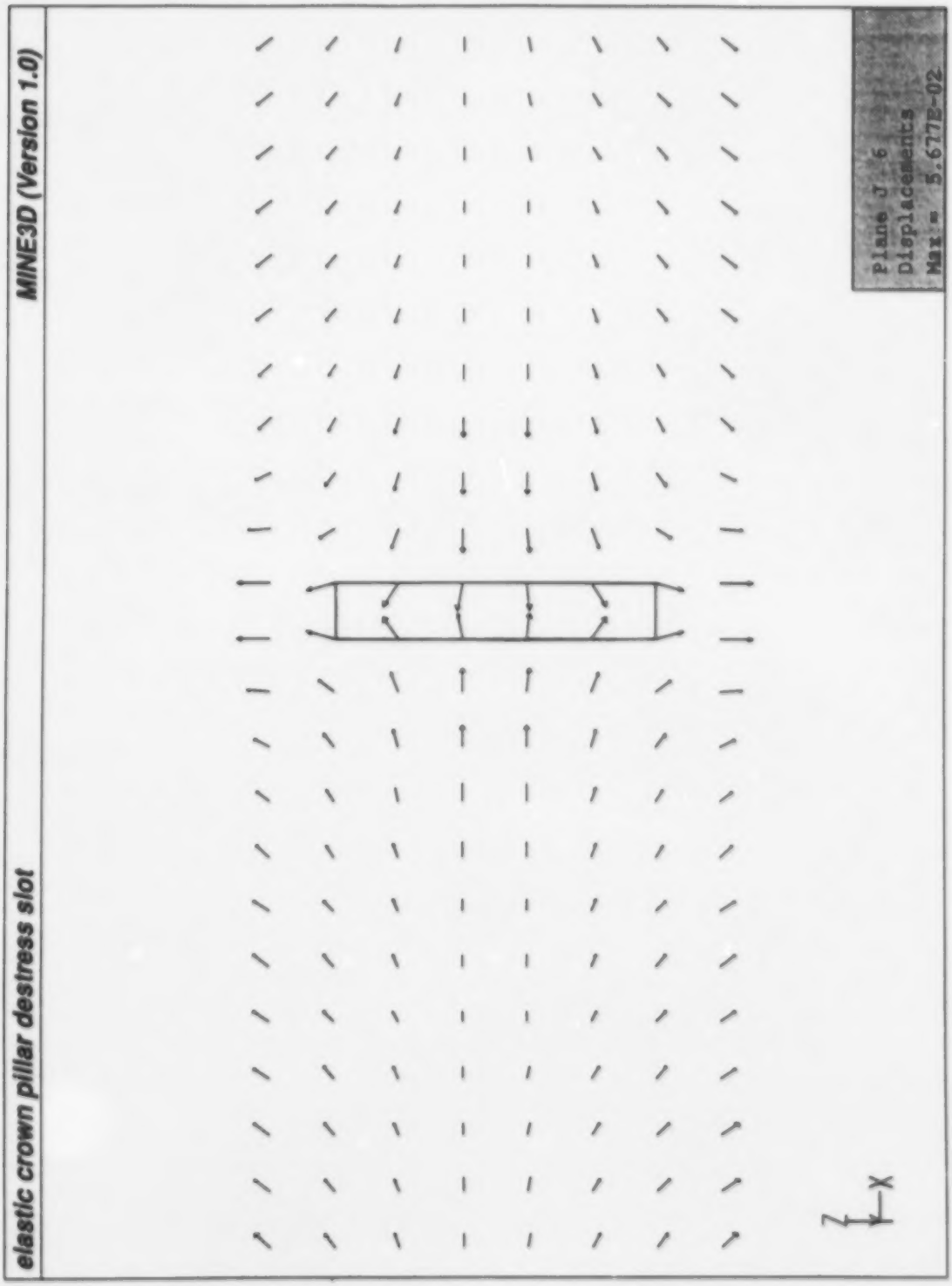

Figure 7-5(a) MINE3D Model:
Displacement Vectors on Vertical Plane Through Destress Slot

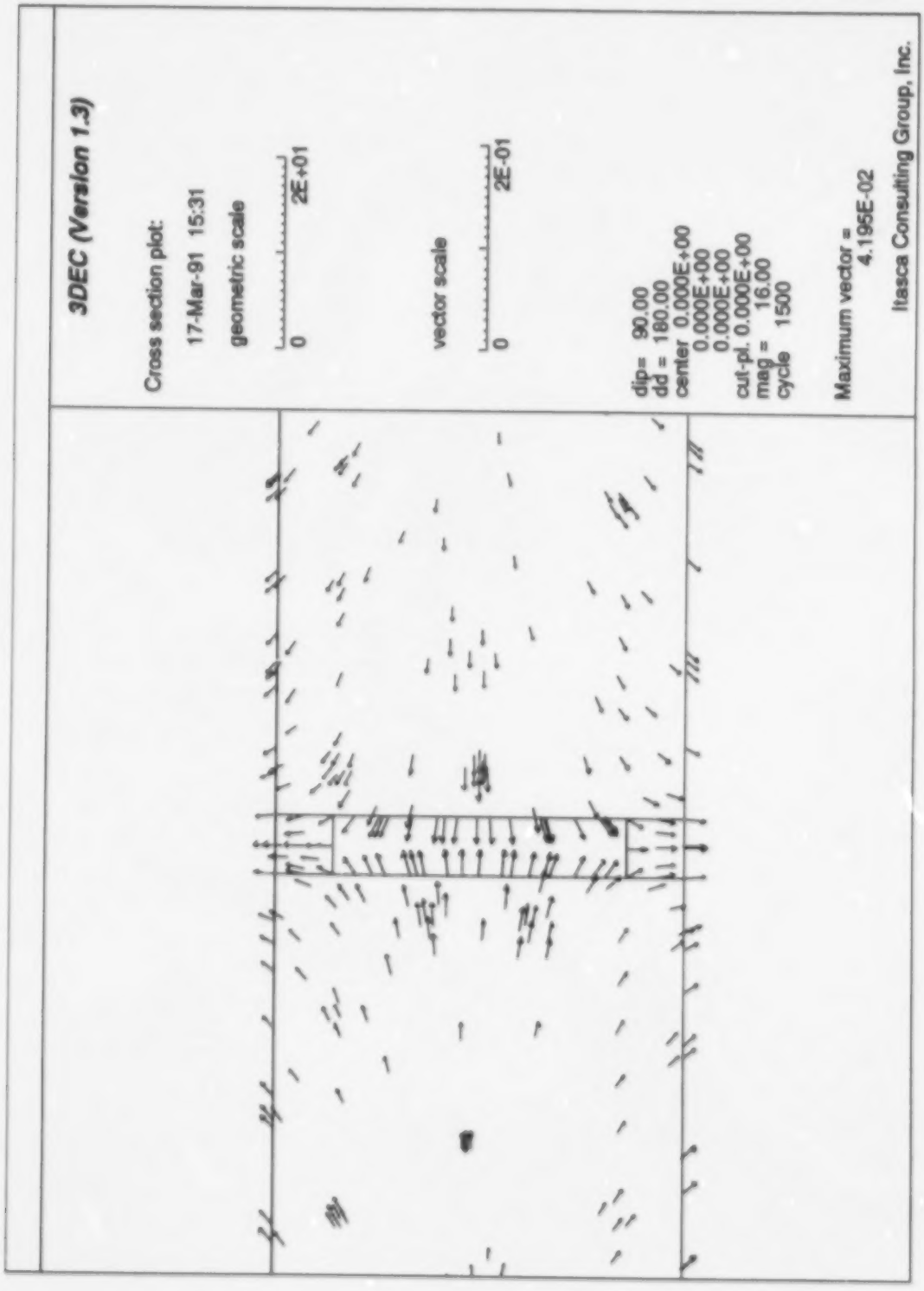

Figure 7-5(b) 3DEC Model:
Displacement Vectors on Vertical Plane Through Destress Slot

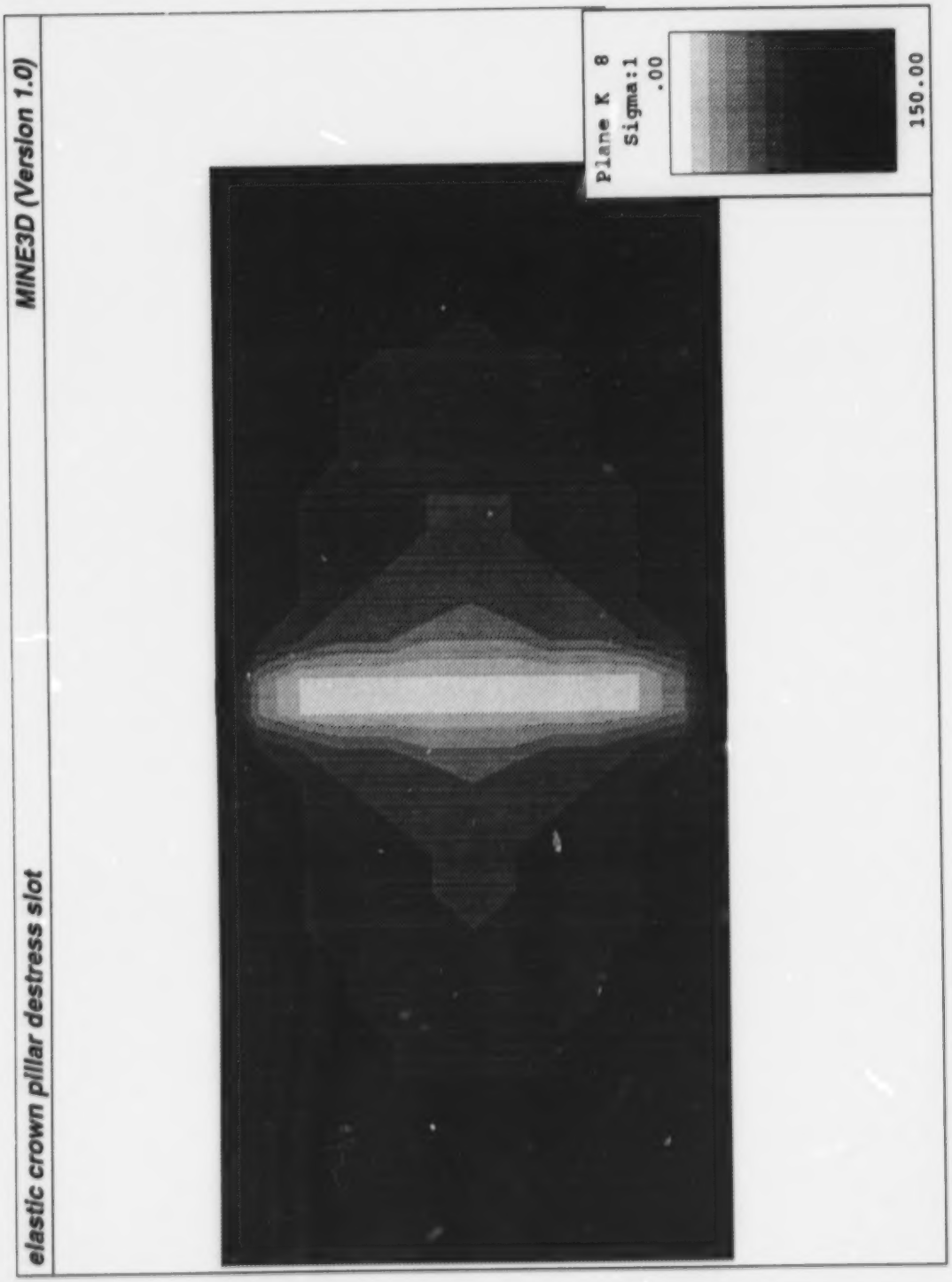

Figure 7-6(a) MINE3D Model:
Principal Stresses on Horizontal Plane Through Destress Slot

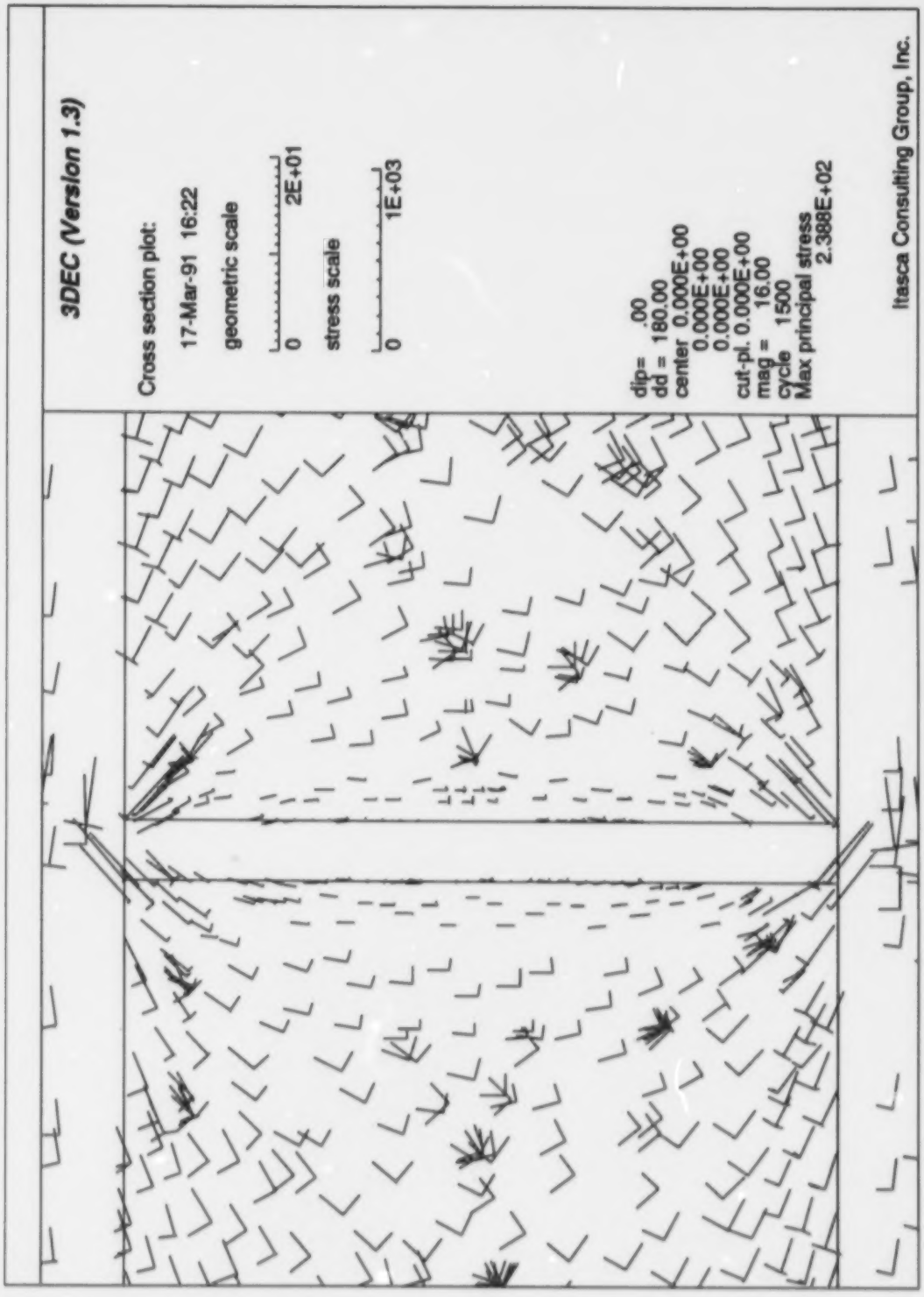

Figure 7-6(b) 3DEC Model:
Principal Stresses on Horizontal Plane Through Destress Slot

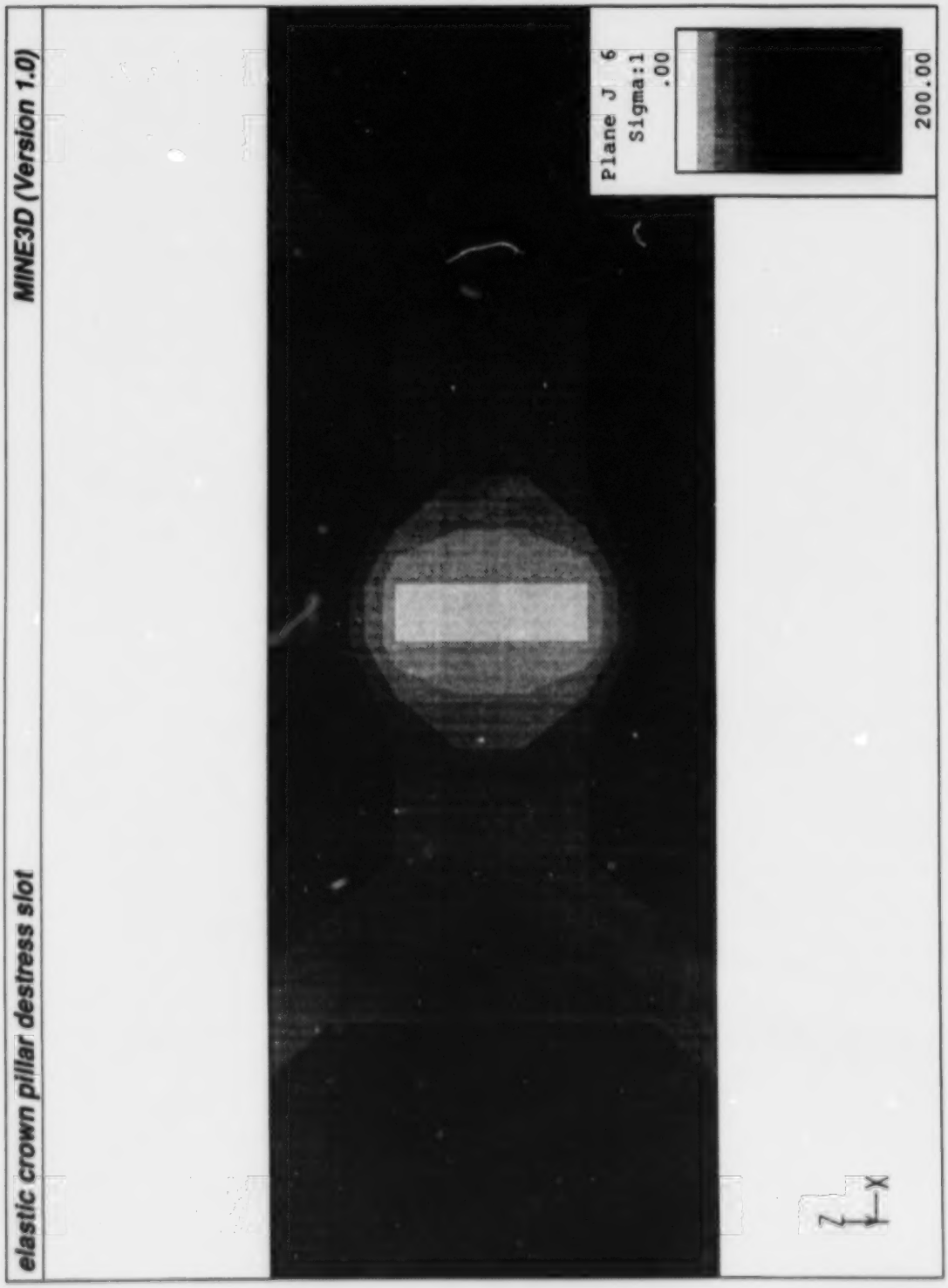

Figure 7-7(a) MINE3D Model:
Principal Stresses on Vertical Plane Through Destress Slot

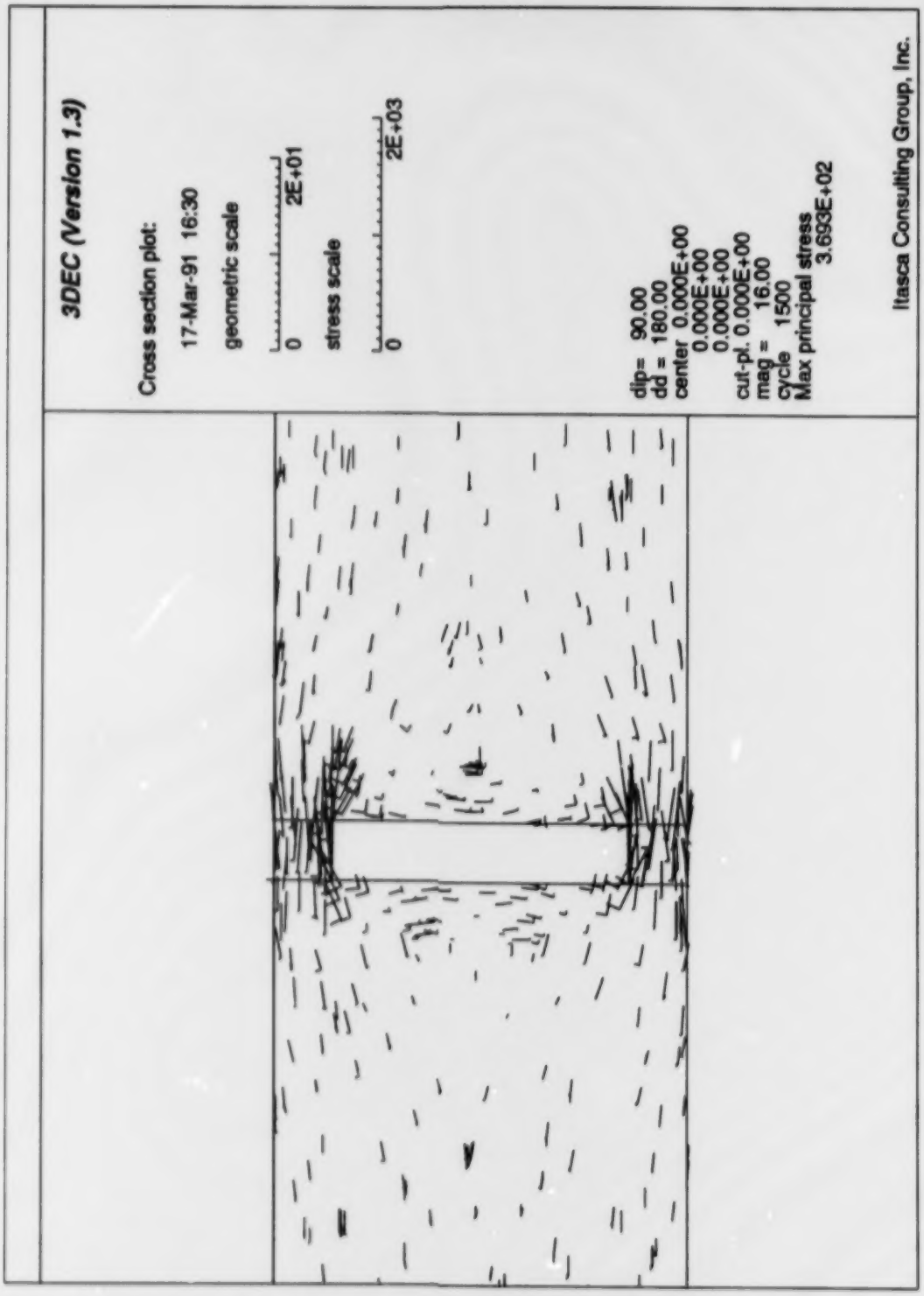

Figure 7-7(b) 3DEC Model:
Principal Stresses on Vertical Plane Through Destress Slot

7.6 Results of 3D Plastic Modelling

The excessive run time required for the MINE3D calculation precluded the performance of a plastic analysis with MINE3D for this problem. It is estimated that a plasticity analysis for the model configuration shown in Figure 7-1 could take three or four weeks (or longer, depending upon the required number of plastic volume elements) with MINE3D on the SUN SPARC2.

The MINE3D analysis, therefore, was out of the question for the present study. However, it seemed prudent to continue the plasticity analysis using the 3DEC code in order to provide insight to the extent of plastic failure which could develop. The 3DEC analysis also can provide an estimation of the progressive change of the stress relaxation zone with each mining stage.

The calculation for stress relaxation in 3DEC is the same as that for FLAC (discussed in Section 5.2.3). Plastic shear failure and tensile failure of any zone in 3DEC will occur when the Mohr-Coulomb yield or tensile strength limit is reached.

The mining stages were modelled using the 3DEC code with the model configuration as shown in Figure 7-2(a,b), but with the strength properties listed in Section 7.2. The 3DEC results for each mining stage, 1 through 8, are presented in terms of two principal stress vector plots. The first plot shows the entire principal stress distribution on either a horizontal or a vertical plane through the slot. The second plot shows the stress distribution only for those zones (as indicated previously in Figure 7-3) which have failed either in shear or in tension. This plot indicates the extent of failure for the given mining stage.

Figure 7-8(a,b) and Figure 7-9(a,b) show the stress state for mining stage 1, i.e. prior to the mining of the destress slot. The results, shown in Figure 7-8(b) and Figure 7-9(b), indicate that a major portion of the crown pillar fails; however, the stresses are still quite high because of the confining effect of the crown pillar between the upper and lower mining blocks.

By introducing the destress slot in mining stage 2, the failure region does not change appreciably, as shown in Figure 7-10(b), but a region of low stress level develops within approximately one slot width around the destress slot, Figure 7-10(a). This stress relaxation zone is a result of the free surface at the slot boundary; also, the stress relaxation zone is confined to the central region around the slot. The remainder of the crown pillar is still under a relatively high stress state.

The 3DEC analysis was continued for mining stages 3 through 8 by creating a model with VRM panels 1 through 6. Figure 7-11(a,b) shows the configuration of the crown pillar region and mining blocks for this model.

Figure 7-12(a) through to Figure 7-17(a) show the resulting stress distribution for each mining stage, as each VRM panel is deleted from the model. Similarly, the failure region for each mining step is presented in Figure 7-12(b) through to Figure 7-17(b).

When VRM panel 1 is removed, stress relaxation is calculated to be located within most of panels 2 and 6. However, a high stress concentration is evidenced in VRM panels 4 and 5. The stresses remain high in these two panels throughout the mining stages. As the Figures indicate, the stress relaxation zone remains a fairly small region around the destress slot while the stresses stay concentrated primarily in the region of panels 4 and 5, throughout the simulation of VRM panel mining.

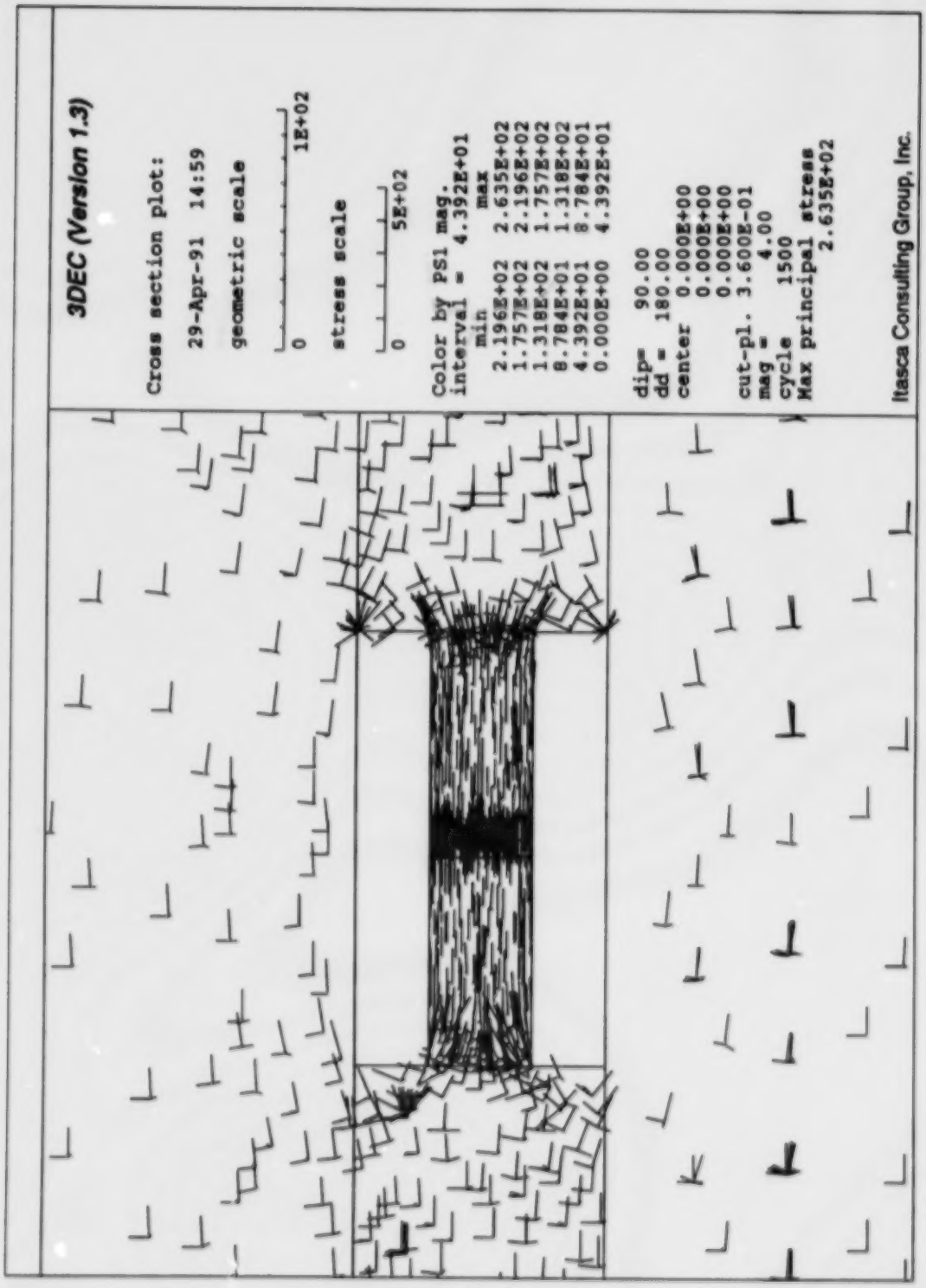

Figure 7-8(a) Projection of Principal Stresses on Plane: Principal Stresses on Vertical Plane Through Destress Slot Mining Stage 1

Figure 7-8(b) Stresses Plotted Within Failed Zones Only: Principal Stresses on Vertical Plane Through Destress Slot Mining Stage 1

Figure 7-9(a) Projection of Principal Stresses on Plane: Principal Stresses on Horizontal Plane Through Crown Pillar Mining Stage 1

Figure 7-9(b) Stresses Plotted Within Failed Zones Only: Principal Stresses on Horizontal Plane Through Crown Pillar Mining Stage 1

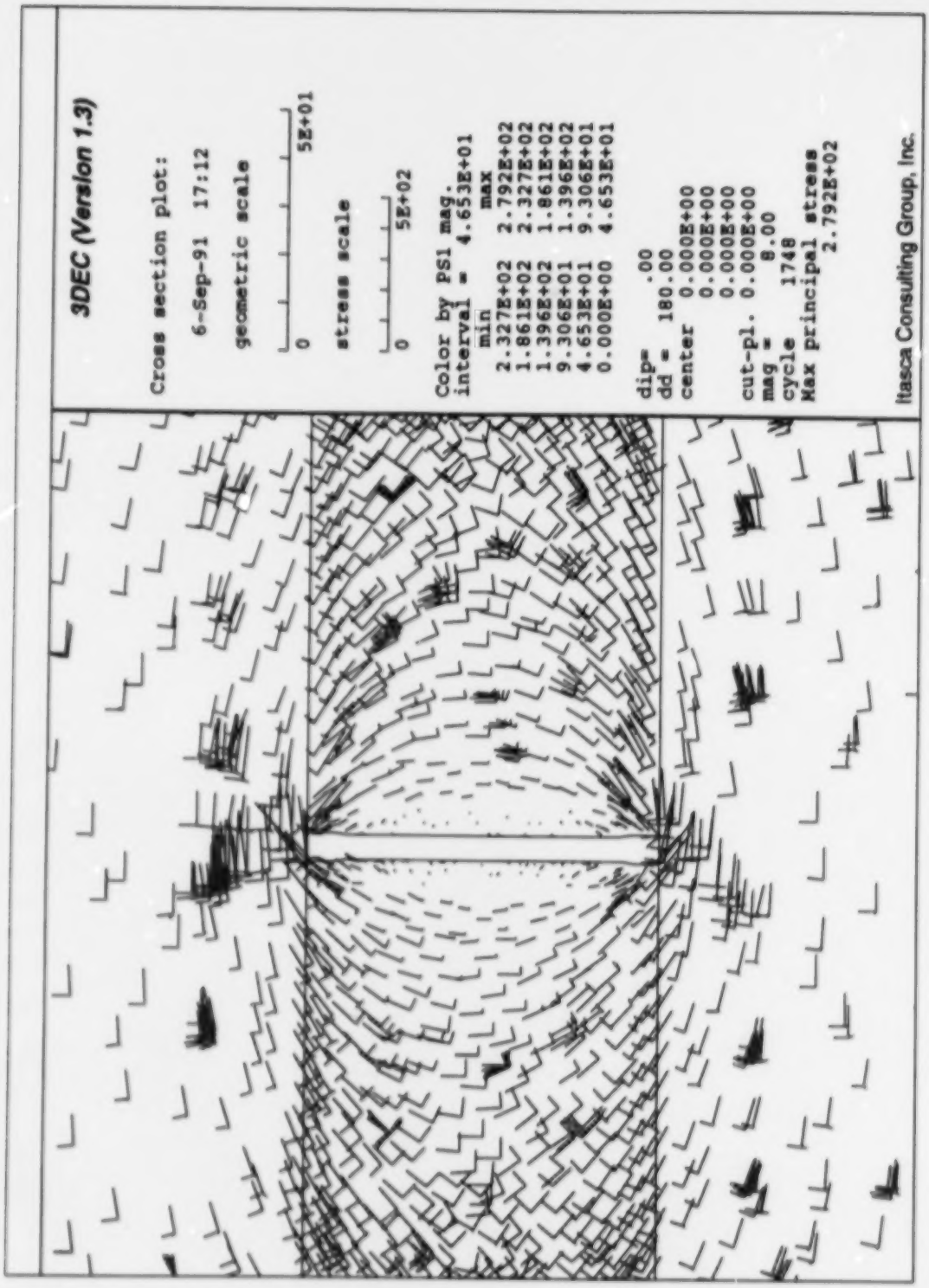

Figure7-10(a) Projection of Principal Stresses on Plane: Principal Stresses on Horizontal Plane Through Crown Pillar Mining Stage 2

Figure 7-10(b) Stresses Plotted Within Failed Zones Only: Principal Stresses on Horizontal Plane Through Crown Pillar Mining Stage 2

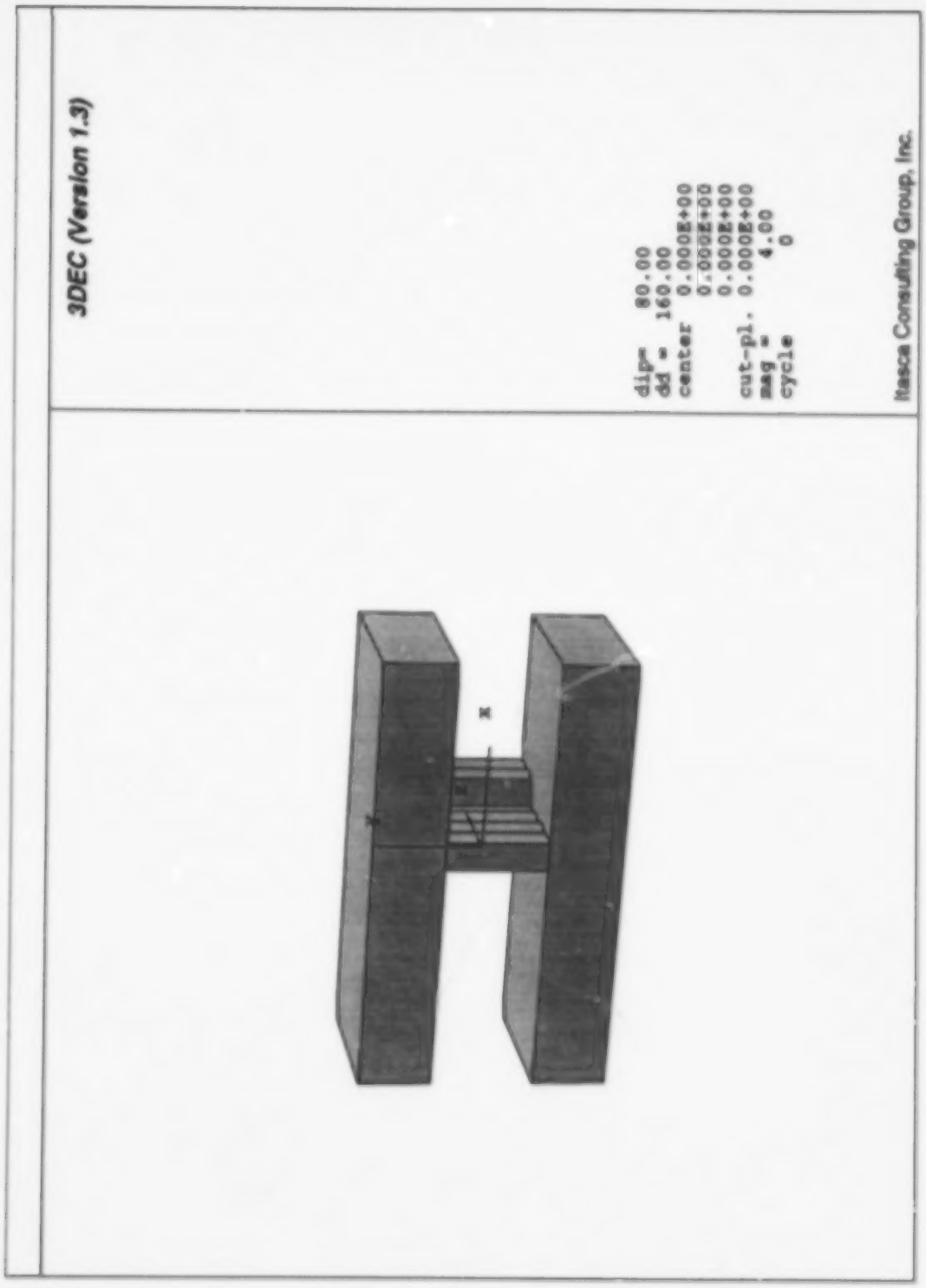

Figure 7-11(a) 3DEC Model of Destress Slot, Upper Mining Block, Lower Mining Block, and VRM Panels

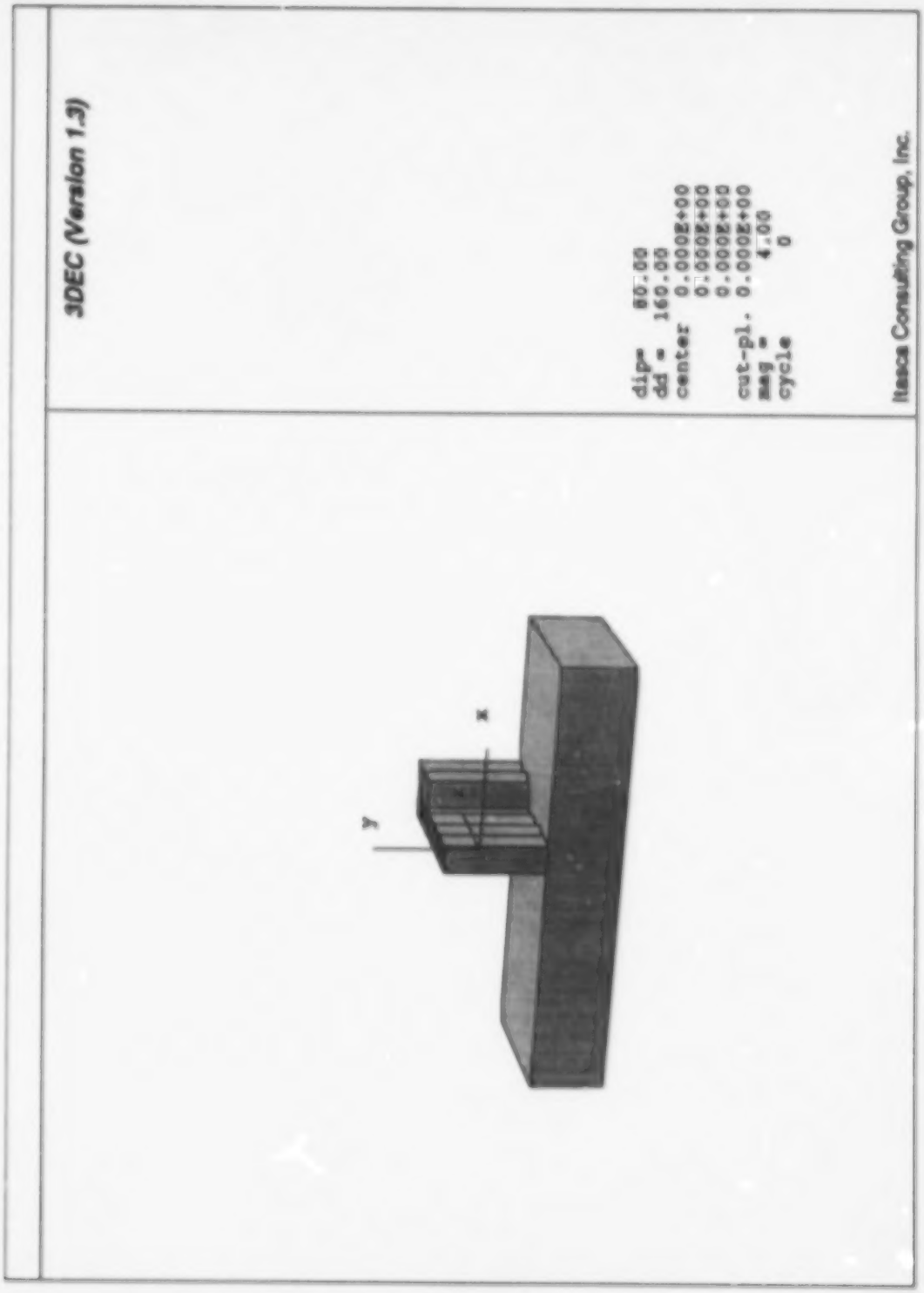

Figure 7-11(b) Upper Mining Block Hidden From View: 3DEC Model of Destress Slot and Mining Panels

Figure 7-12(a) Projection of Principal Stresses on Plane: Principal Stresses on Horizontal Plane Through Crown Pillar Mining Stage 3

Figure 7-12(b) Stresses Plotted Within Failed Zones Only: Principal Stresses on Horizontal Plane Through Crown Pillar Mining Stage 3

Figure 7-13(a) Projection of Principal Stresses on Plane: Principal Stresses on Horizontal Plane Through Crown Pillar Mining Stage 4

Figure 7-13(b) Stresses Plotted Within Failed Zones Only: Principal Stresses on Horizontal Plane Through Crown Pillar Mining Stage 4

Figure 7-14(a) Projection of Principal Stresses on Plane: Principal Stresses on Horizontal Plane Through Crown Pillar Mining Stage 5

Figure 7-14(b) Stresses Plotted Within Failed Zones Only: Principal Stresses on Horizontal Plane Through Crown Pillar Mining Stage 5

Figure 7-15(a) Projection of Principal Stresses on Plane: Principal Stresses on Horizontal Plane Through Crown Pillar Mining Stage 6

Figure 7-15(b) Stresses Plotted Within Failed Zones Only: Principal Stresses on Horizontal Plane Through Crown Pillar Mining Stage 6

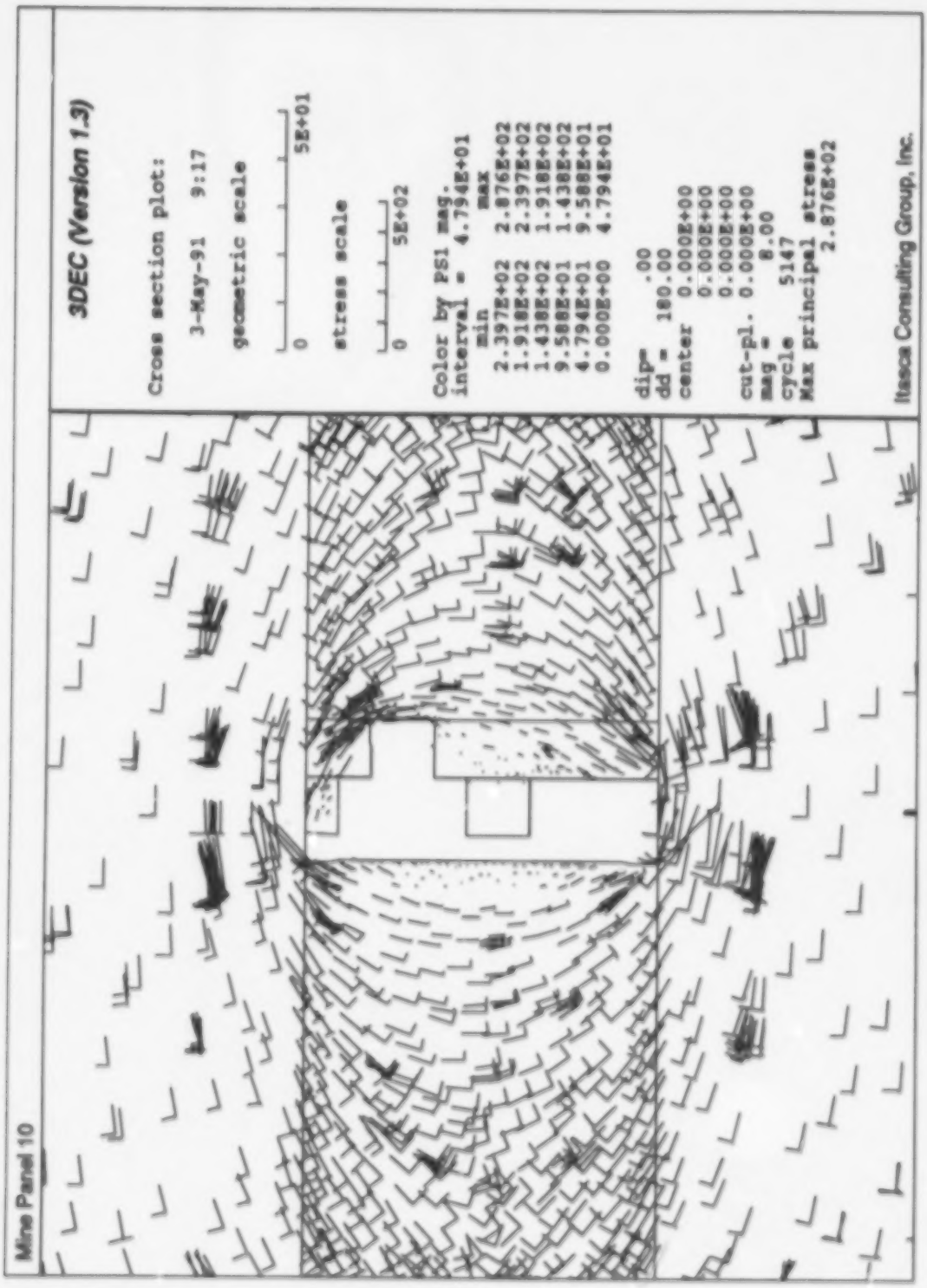

Figure 7-16(a) Projection of Principal Stresses on Plane: Principal Stresses on Horizontal Plane Through Crown Pillar Mining Stage 7

Figure 7-16(b) Stresses Plotted Within Failed Zones Only: Principal Stresses on Horizontal Plane Through Crown Pillar Mining Stage 7

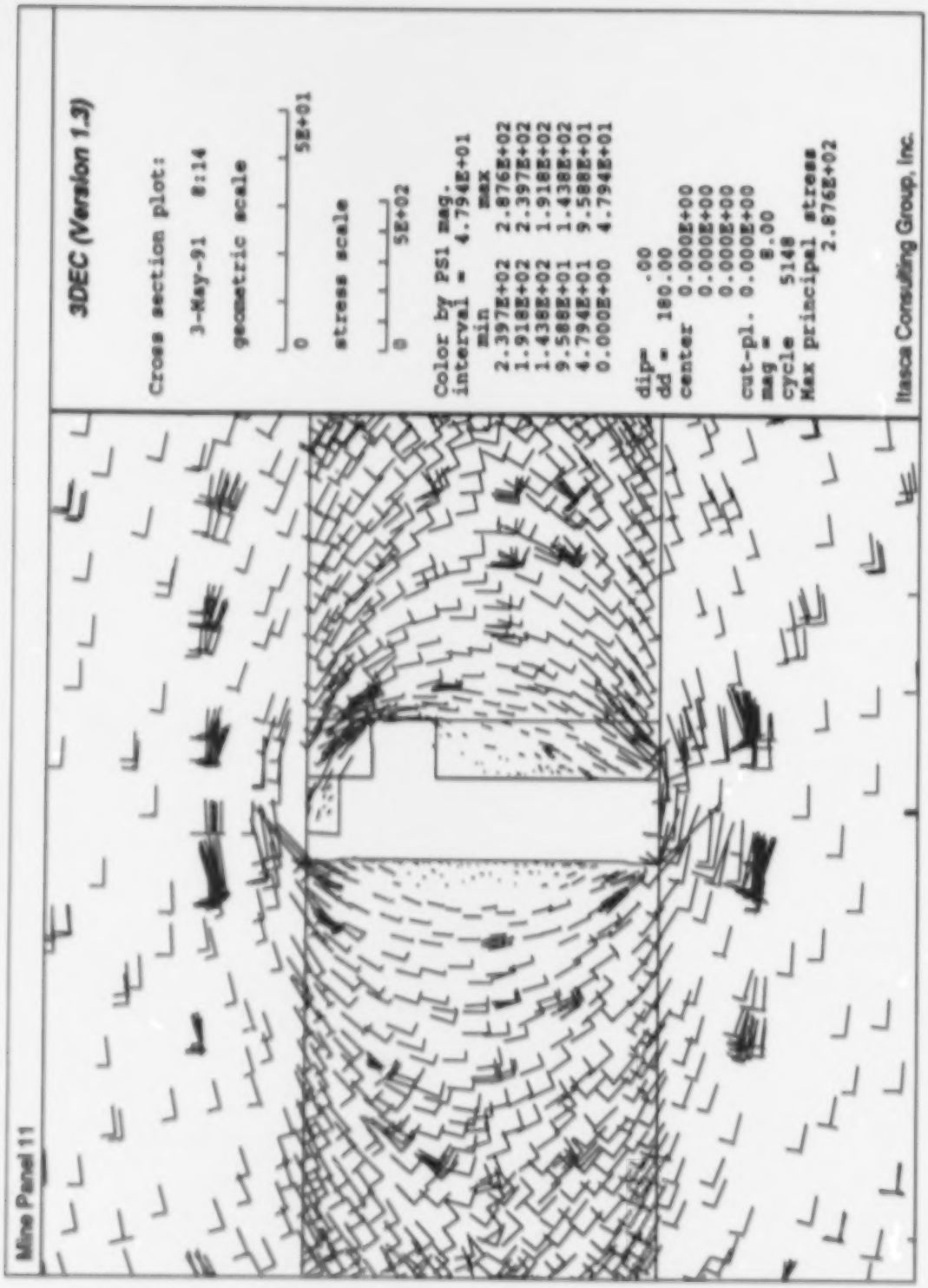

Figure 7-17(a) Projection of Principal Stresses on Plane: Principal Stresses on Horizontal Plane Through Crown Pillar Mining Stage 8

Figure 7-17(b) Stresses Plotted Within Failed Zones Only: Principal Stresses on Horizontal Plane Through Crown Pillar Mining Stage 8

7.7 Summary of the MINE3D Modelling

Based upon the results of the 3DEC analysis, it is evident that plastic volume elements would be required throughout most of the crown pillar in order to model the plastic failure region adequately. This presents a modelling dilemma for MINE3D because the required element length must be small to represent the thickness of the destress slot (smaller than approximately 7 meters), while the total volume of mining blocks is quite large (roughly 10 to 15 million cubic meters).

The 3DEC analysis suggests that the influence of the upper and lower mining blocks on the stress concentration within the crown pillar may be substantial. Therefore, the development of a representative MINE3D model on the same scale as the BEM3D model, but with plastic volume elements within the crown pillar region, would require at least 700,000 parallelepiped nodes, assuming an element length of 3 meters. As a result, roughly 16 GBytes of computer memory would be required for coefficient storage for this model. (See Section 4.3 of Volume 2).

If the general boundary element scheme used in BEM3D were extended to include volume elements, the storage requirement would be even greater than the 16 GBytes. For the model described in Section 4 of this report, the storage requirements would be of the order of 40 to 50 GBytes if volume elements were added in the crown pillar region. (See Section 4.10 of Volume 2 for a discussion on boundary element storage requirements.)

A model can be generated with MINE3D similar to that for BEM3D (see, for example, Figure 7-18). This model consists of approximately 10,000 parallelepiped nodes and 2000 surface nodes, and requires roughly 240 MBytes storage. The element size (20 meters) is too coarse for adding volume elements for a plasticity analysis.

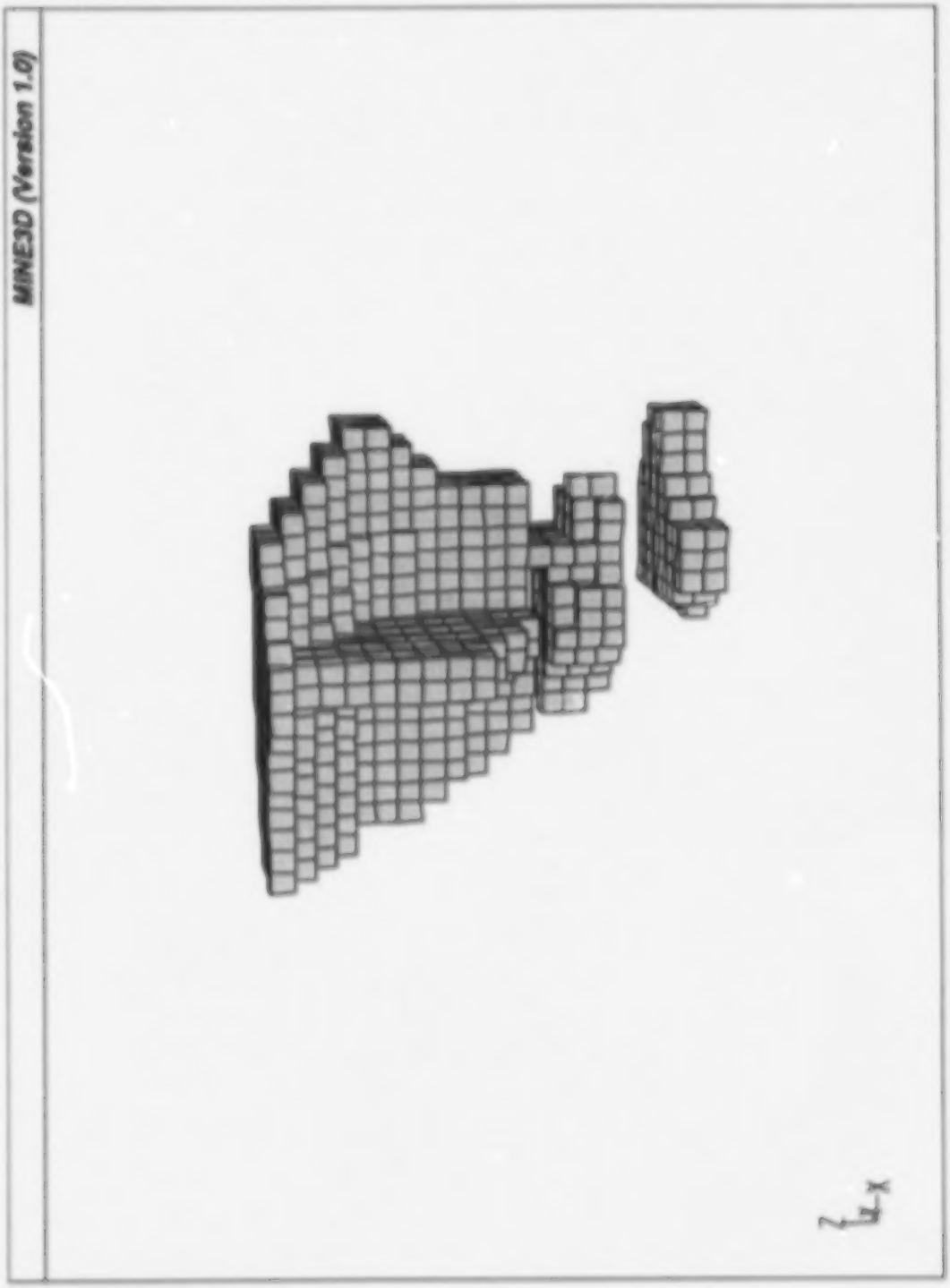

Figure 7-18 MINE3D Model of Creighton Mine

8.0 COMPARISON OF THE NUMERICAL MODELLING STUDIES

The purpose of this numerical modelling calibration study was to attempt to simulate rock mass response to bulk mining such that the modelling results would echo the field monitoring portion of this project, Volume 3. Once the numerical models were fully calibrated, the resulting rock mass properties would be used as input parameters to a 3-dimensional, elasto-plastic boundary element model called MINE3D. The final set of input parameters, Table 5-12, describes the case study site. These values are intended for the MINE3D modelling of the case study site in order to verify the code.

There were five distinctly different numerical modelling codes used in the calibration modelling, each of them simulating rock mass response within the 4500 VRM mining block. The numerical modelling codes that were used in the calibration modelling are as follows: BEM3D, FLAC, BEM2D, MINE2D, and 3DEC.

Throughout the 4½ years of mining within the 4500 VRM ore block, an extensive use of monitoring instrumentation has allowed the determination of the stress changes, rock mass displacements, and the location of stress relaxation zones (associated with the progressive ore removal). The methodology of calibration subsequently involved the comparison of numerical modelling results to this accumulation of instrumentation data. The monitoring information has also assisted in providing an understanding of the rock mass response to mining.

The results of the modelling, outlined in detail within the previous sections of this Volume 4, has not only demonstrated the ability of each of the numerical codes to accurately simulate the rock mass response, but the results have also illustrated the limitations of each code to doing so.

In summary, BEM3D numerical modelling has clearly demonstrated the ability of the elastic, boundary element program in providing only a generalized rock mass response to mining. Two obvious short comings of the BEM3D program are the elastic formulation and the continuum code. Since this code cannot simulate progressive failure of the rock mass because of the elastic formulation, neither can it determine the stress redistributions which would occur as a result of failure.

As far as being a continuum code, BEM3D is not able to calculate displacement/discontinuity movements. Block movements played a major role within the case study site, and these occurrences could not be reproduced using BEM3D. Due to these two major restrictions within the BEM3D numerical code, the calibration of the case study model was subsequently based on limited comparisons with the monitoring data.

With regard to the borehole camera work, it was evident that the joints within the rock mass surrounding the panel openings were loose and open; this area of the rock mass was termed as being "relaxed". It was also noted that the extent of the relaxed area was dependent on the amount of mining that had taken place. Even though the boundary between the relaxed and the highly stressed ground was easily discernable with the borehole camera, it was impossible to distinguish between stress relaxation caused by stress redistribution after failure of the rock mass or unloading caused by a stress shadow effect.

For the prediction of rock mass failure, the 3D elastic program estimates the area of failed ground with a Factor of Safety Contour Plot whereby a safety contour line of 1.0 denotes the boundary between failed and intact ground. Using just the factor of safety contour of 1.0, the elastic model continually underestimates the area of failed ground, as would be expected for a purely elastic formulation. Despite this discrepancy with the safety factor contouring, the BEMJD models were able to be calibrated against the borehole camera work for the entire mining sequence in the case study site.

The information collected from the underground stress monitoring program was limited, and therefore only some of this data could be used for the calibration of the BEMJD models. However, of great importance to the case study monitoring, and subsequent calibrations, were the extensometer readings and the inclinometer data. This data indicated sudden and large movements of blocks (up to 4" in places) and because the BEMJD program is a continuum code, none of this monitoring data could be utilized in the calibration methodology. As a consequence of the extensometer and inclinometer monitoring, it became quite evident that the mode of failure and the mechanisms taking place within the 4500 ore block were related to block movement. Unfortunately, the displacements cannot even be remotely reproduced nor simulated with the BEMJD code; this is another limitation of the program with this particular application for numerical modelling.

In summary for the FLAC, BEM2D and MINE2D numerical modelling, a major limitation is the extremely poor representation of the three-dimensional geometry with the two-dimensional codes. The geometry of the ore zone and mining areas in and around the case study site is far from simple; in fact, there is no ideal section through the mining areas which meet the required plane-strain conditions for 2D modelling. Even before attempting to calibrate the crown pillar failure and the rock mass response to mining within the 4500 ore block, the 2D models were non-representative of the underground environment.

For modelling the failure of a mine geometry which cannot be resolved into a valid two-dimensional section, the MINE3D model is a better choice.

Additional to the geometry problems encountered with the 2D sections, the BEM2D code experienced problems with the elasticity and continuum nature of the formulation. These problems greatly limited the usage of BEM2D for the case study modelling.

Another limitation with the 2D modelling, experienced only with FLAC, was the problem of model size. The crown pillar itself was not a concern, however, the areas of mining which surround the crown are extremely extensive. In order to take all of these pre-mining effects into account, while at the same time attempting to achieve a high level of accuracy within the comparatively smaller crown pillar region, an extremely large grid is required. A FLAC model which simulates areas of mining throughout the entire mine, but also models the crown pillar with fine zoning, would be tremendously large and would consequently require unacceptably large run-times. Due to time constraints with the project, a model of the entire mine was rejected. Only a smaller area of the mine was modelled using FLAC, with the knowledge that a great proportion of the pre-mining effects were not initialized within the model, and thus the accuracy of the results were reduced.

As far as calibration of the two-dimensional plasticity codes (FLAC and MINE2D), the displacement/discontinuity movements that were observed underground were not simulated within the models. The FLAC code, like the BEM3D and BEM2D codes, is a continuum and cannot simulate discontinuities. However, the displacements that were predicted from the FLAC model were within 30% of those measured underground.

For calibration with the failure of the rock mass, both the FLAC and the MINE2D modelling required a 50% decrease in the vertical stress transfer through the backfill in the upper (6400-6600 level) ore block and the lower (6700-6800 level) ore block. The height of the crown pillar failure was accurately calibrated with both of the models (90 feet), however, the mode of crown pillar failure could not be simulated in any section for either of the modelling codes. FLAC and MINE2D both predicted crown failure which was gradual; the failure originated at the footwall contact on the 6700 level and progressed in a shearing mode up to the hangingwall contact at the 6600 level. The assumed failure of the crown pillar was sudden, with the occurrence of a rockburst in October 1987, yet there was no method of simulating this failure in these numerical models.

In summary for the 3DEC code, the model was able to simulate the mining and the subsequent 90-foot crown pillar failure using the same input parameters as the 2D calibrated models, Table 5-12. This code is highly suited for the case study calibration modelling because of the three-dimensionality, the elastic/plastic formulation, as well as the ability to simulate displacements and discontinuities. The actual 3D&C simulations, however, did not take advantage of the discontinuity capabilities because of the required comparisons with the MINE3D modelling.

Once the 3DEC model was calibrated, the results were examined to determine the extent of plastic behaviour within the crown pillar. This information, regarding the extent of plasticity elements, was required for the set-up and running of the MINE3D model of the case study site. It was determined from 3DEC that the majority of the crown pillar experienced some plastic behaviour due to mining activity in the other areas of the mine.

Since a large proportion of the elements within the crown pillar required plasticity calculations, the MINE3D model had to be greatly reduced in size. This reduction in the size of the MINE3D model was due to the primary limitation with the code: plasticity calculations require considerable computer space and lengthy run-times. As the number of plasticity elements increase, the longer it will take to solve the calculations within the model and the more space the computer must have. With the given time constraints for this modelling project, as well as the limitations with present computer hardware, the only MINE3D model which could be run was the crown pillar area in which the surrounding mining effects were neglected. Since much of the surrounding mining influences were not initialized within the MINE3D model, the resulting set of input parameters can be considered questionable.

With regard to the modelling of the case study site, some of the main limitations found with the other numerical codes are overcome with MINE3D. MINE3D is three-dimensional and it has the capability for determining elasto-plastic behaviour of the rock mass. The problems experienced with the verification modelling of the MINE3D code can be attributed to the case study site itself. The selected study area is a highly complex region for modelling, and the monitoring program indicated that discontinuities play a major role in the nature of the deformation which occurred within the rock mass. In order to exactly reproduce this rock mass response within the case study area, the block movements should be represented. Unfortunately, MINE3D does not have the capability for simulating the behaviour of discontinuities, partially because of the time constraints on the project but also because the boundary element method itself is not well-suited to simulating discontinuities. The case study modelling also requires the simulation of the effect of excavations in other parts of the mine prior to simulating the 4500 ore block mining. A model which includes both the surrounding mining as well as the many plasticity elements within the crown pillar is unacceptably large for present day computer hardware to compute within moderate time limits.

There are two avenues which may be pursued for further development of this numerical modelling program. Either the MINE3D plasticity calculations could be enhanced in order to handle a large number of plasticity elements within reasonable time constraints, or the MINE3D code could be applied to a much simpler mining geometry. With the application to a simpler study area, the program would be a valuable tool for simulating rock mass response to mining.

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APPENDIX A

Program Bem 3.0
Job Description
Creighton Deep Destress Slot Mining Only 13-DEC-90
17:42:28

Job Date 13-dec-90
Job Time 17:42:28

Control Parameters
Symmetry = 0 for no symmetry
= 1 for reflection such that x <=> -x
= 2 for reflection such that x <=> -x and y <=> -y
= 3 for reflection such that x <=> -x and y <=> -y and z <=> -z

Number of Load Steps	Number of Iterations	Relaxation Parameter Maximum	Relaxation Parameter Minimum	Stress Tolerance	Symmetry Planes
1	1000	1.000	0.500	1.000	0

Element Incidence List
Use a zero element number to end the list
Element Type = 1 for surface stress discontinuity
= 2 for surface displacement discontinuity
= 3 for volume stress discontinuity
Straight Element = 0
Curved Element = 1

Elem #	Coordinate Number Incidences 1	2	3	4	5	6	7	8	# Div Between 1-2	2-3	1-5	Elem Type	Curv Line	Thick/ Height
6000-6200														
1	1	5	6	2	21	25	26	22	3	1	2	1	1	0.00
2	2	6	7	3	22	26	27	23	3	2	2	1	1	0.00
3	4	8	9	5	24	28	29	25	2	3	2	1	1	0.00
4	5	9	10	6	25	29	30	26	2	1	2	1	1	0.00
5	6	10	11	7	26	30	31	27	2	2	2	1	1	0.00
6	10	12	13	11	30	32	33	31	1	2	2	1	1	0.00
7	12	14	15	13	32	34	35	33	1	2	2	1	1	0.00
8	14	16	17	15	34	36	37	35	1	2	2	1	1	0.00
9	16	18	19	17	36	38	39	37	2	2	2	1	1	0.00
6200-6400														
10	21	25	26	22	41	45	46	42	3	1	2	1	2	0.00
11	22	26	27	23	42	46	47	43	3	3	2	1	2	0.00
12	24	28	29	25	44	48	49	45	2	3	2	1	2	0.00
13	25	29	30	26	45	49	50	46	2	1	2	1	2	0.00
14	26	30	31	27	46	50	51	47	2	3	2	1	2	0.00
15	30	32	33	31	50	52	53	51	1	1	2	1	2	0.00
16	32	34	35	33	52	54	55	53	1	1	2	1	2	0.00
17	34	36	37	35	54	56	57	55	1	1	2	1	2	0.00
18	36	38	39	37	56	58	59	57	2	1	2	1	2	0.00
6400-6600														
19	41	45	46	42	61	65	66	62	4	4	4	1	3	0.00
20	42	46	47	43	62	66	67	63	4	5	4	1	3	0.00

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    21   44   48   49   45   64   68   69   65    3    3    4    1    3   0.00
    22   45   49   50   46   65   69   70   66    3    3    4    1    3   0.00
    23   46   50   51   47   66   70   71   67    3    5    4    1    3   0.00
    24   50   52   53   51   70   72   96   71    3    8    6    1    3   0.00
    25   52   54   55   53   72   74   97   96    3    8    6    1    3   0.00
    26   54   56   57   55   74   76  170   97    4    8    6    1    3   0.00
    27   56   58   59   57   76   78   79  170    4    7    4    1    3   0.00
*6700-6800 4300 block
    28   81   83   84   81  101  103  104  101    3    5    3    1    4   0.00
    29   82   85   86   83  102  105  106  103    5    3    3    1    4   0.00
    30   83   86   87   84  103  106  107  104    5    5    3    1    4   0.00
* 6700-6800 next to destress slot
    31   86   88   98   87  106  108  109  107    2    7    4    1    4   0.00
    32   88   90   99   98  108  110  111  109    2    7    4    1    4   0.00
    33   90   92   93   99  110  112  113  111    2    7    4    1    4   0.00
    34   92   94   95   93  112  114  115  113    2    4    2    1    4   0.00
*6900-7000
    35  121  123  124  122  131  133  134  132    2    5    2    1    5   0.00
    36  123  125  126  124  133  135  136  134    2    5    2    1    5   0.00
    37  125  127  128  126  135  137  138  136    3    5    2    1    5   0.00
    38  127  129  130  128  137  139  140  138    2    4    2    1    5   0.00
*  joiner plate destress slot and mining above
    39   72   74   97   96  159  160   97   96    2    5    2    1    5   0.00
*  destress slot all 5 panels
    40  159  160   97   96   88   90   99   98    2   10    6    1    6   0.00
*  joiner plate and 1290
    41   94   95  115  114  116  117  119  118    2    5    5    1    4   0.00
*  1290 mining first 2 panels
    42  116  117  119  118  120  161  163  162    3    3    5    1    4   0.00
*  joiner plate between top panel 1 and 4400 mining
    43   74   76  170   97  168  169  170  173    2   10    2    1    5   0.00
*  joiner plate side of destress slot and panel 1
    44  168  166  172  173  160   90   99   97    6    8    4    1    5   0.00
*  joiner plate bottom panel 1 and 4400 mining
    45  166  167  171  172   90   92   93   99    5    4    3    1    5   0.00
*  panel 1
    46  168  169  170  173  166  167  171  172    5    6    6    1    6   0.00
     0/
* ---------------------------------------------------------------------------
* Coordinate Data List
* Use a zero coordinate number to end the list
* T x-y is measured counterclockwise from the X-axis to the Y-axis
* T z-xy is measured from the Z-axis down to the X-Y plane
* |----|----------|----------|----------|----------|----------|----------|
* |Coor|    X     |    Y     |    Z     |  Radius  |  Angle   |  Angle   |
* | #  |  Coord   |  Coord   |  Coord   |    R     |  T x-y   |  T z-xy  |
* |----|----------|----------|----------|----------|----------|----------|
* 6000
     1     3600.00     6020.00    -6000.00        0.00        0.00        0.00
     2     3600.00     6020.00    -6000.00        0.00        0.00        0.00
     3     3600.00     6350.00    -6000.00        0.00        0.00        0.00

     4     3850.00     5970.00    -6000.00        0.00        0.00        0.00
     5     3850.00     5970.00    -6000.00        0.00        0.00        0.00
```

6	3850.00	5970.00	-6000.00	0.00	0.00	0.00
7	3850.00	6180.00	-6000.00	0.00	0.00	0.00
8	4050.00	5880.00	-6000.00	0.00	0.00	0.00
9	4050.00	5880.00	-6000.00	0.00	0.00	0.00
10	4050.00	5880.00	-6000.00	0.00	0.00	0.00
11	4050.00	6070.00	-6000.00	0.00	0.00	0.00
12	4130.00	5860.00	-6000.00	0.00	0.00	0.00
13	4130.00	6070.00	-6000.00	0.00	0.00	0.00
14	4180.00	5840.00	-6000.00	0.00	0.00	0.00
15	4180.00	6080.00	-6000.00	0.00	0.00	0.00
16	4230.00	5810.00	-6000.00	0.00	0.00	0.00
17	4230.00	6020.00	-6000.00	0.00	0.00	0.00
18	4320.00	5770.00	-6000.00	0.00	0.00	0.00
19	4320.00	5980.00	-6000.00	0.00	0.00	0.00
20	4320.00	5980.00	-6000.00	0.00	0.00	0.00
6200						
21	3730.00	6000.00	-6200.00	0.00	0.00	0.00
22	3730.00	6100.00	-6200.00	0.00	0.00	0.00
23	3730.00	6350.00	-6200.00	0.00	0.00	0.00
24	4210.00	5770.00	-6200.00	0.00	0.00	0.00
25	4140.00	6000.00	-6200.00	0.00	0.00	0.00
26	4140.00	6100.00	-6200.00	0.00	0.00	0.00
27	4140.00	6260.00	-6200.00	0.00	0.00	0.00
28	4360.00	5770.00	-6200.00	0.00	0.00	0.00
29	4360.00	6000.00	-6200.00	0.00	0.00	0.00
30	4360.00	6100.00	-6200.00	0.00	0.00	0.00
31	4360.00	6280.00	-6200.00	0.00	0.00	0.00
32	4420.00	6080.00	-6200.00	0.00	0.00	0.00
33	4420.00	6290.00	-6200.00	0.00	0.00	0.00
34	4480.00	6080.00	-6200.00	0.00	0.00	0.00
35	4480.00	6310.00	-6200.00	0.00	0.00	0.00
36	4530.00	6060.00	-6200.00	0.00	0.00	0.00
37	4530.00	6340.00	-6200.00	0.00	0.00	0.00
38	4740.00	6020.00	-6200.00	0.00	0.00	0.00
39	4740.00	6270.00	-6200.00	0.00	0.00	0.00
40	4740.00	6270.00	-6200.00	0.00	0.00	0.00
6400						
41	3880.00	6070.00	-6400.00	0.00	0.00	0.00
42	3880.00	6180.00	-6400.00	0.00	0.00	0.00
43	3880.00	6480.00	-6400.00	0.00	0.00	0.00
44	4290.00	5780.00	-6400.00	0.00	0.00	0.00
45	4230.00	6050.00	-6400.00	0.00	0.00	0.00

	46	4230.00	6160.00	-6400.00	0.00	0.00	0.00
	47	4230.00	6420.00	-6400.00	0.00	0.00	0.00
	48	4370.00	5780.00	-6400.00	0.00	0.00	0.00
	49	4370.00	6050.00	-6400.00	0.00	0.00	0.00
	50	4370.00	6160.00	-6400.00	0.00	0.00	0.00
	51	4370.00	6390.00	-6400.00	0.00	0.00	0.00
	52	4450.00	6150.00	-6400.00	0.00	0.00	0.00
	53	4450.00	6360.00	-6400.00	0.00	0.00	0.00
	54	4500.00	6150.00	-6400.00	0.00	0.00	0.00
	55	4500.00	6320.00	-6400.00	0.00	0.00	0.00
	56	4550.00	6140.00	-6400.00	0.00	0.00	0.00
	57	4550.00	6300.00	-6400.00	0.00	0.00	0.00
	58	4730.00	6130.00	-6400.00	0.00	0.00	0.00
	59	4730.00	6230.00	-6400.00	0.00	0.00	0.00
	60	4730.00	6230.00	-6400.00	0.00	0.00	0.00
6600							
	61	4080.00	6060.00	-6580.00	0.00	0.00	0.00
	62	4080.00	6230.00	-6580.00	0.00	0.00	0.00
	63	4080.00	6500.00	-6580.00	0.00	0.00	0.00
	64	4280.00	5950.00	-6580.00	0.00	0.00	0.00
	65	4280.00	6030.00	-6580.00	0.00	0.00	0.00
	66	4280.00	6230.00	-6580.00	0.00	0.00	0.00
	67	4280.00	6480.00	-6580.00	0.00	0.00	0.00
	68	4350.00	5950.00	-6580.00	0.00	0.00	0.00
	69	4350.00	6030.00	-6580.00	0.00	0.00	0.00
	70	4380.00	6180.00	-6580.00	0.00	0.00	0.00
	71	4380.00	6450.00	-6580.00	0.00	0.00	0.00
	72	4405.00	6230.00	-6570.00	0.00	0.00	0.00
	73	4405.00	6450.00	-6570.00	0.00	0.00	0.00
	74	4435.00	6230.00	-6570.00	0.00	0.00	0.00
	75	4435.00	6450.00	-6570.00	0.00	0.00	0.00
	76	4480.00	6230.00	-6570.00	0.00	0.00	0.00
	77	4480.00	6480.00	-6570.00	0.00	0.00	0.00
	78	4660.00	6230.00	-6570.00	0.00	0.00	0.00
	79	4660.00	6430.00	-6570.00	0.00	0.00	0.00
	80	4660.00	6430.00	-6570.00	0.00	0.00	0.00
6700							
	81	4070.00	6400.00	-6684.00	0.00	0.00	0.00
	82	4180.00	6230.00	-6684.00	0.00	0.00	0.00
	83	4160.00	6300.00	-6684.00	0.00	0.00	0.00
	84	4180.00	6460.00	-6684.00	0.00	0.00	0.00

85	4350.00	6230.00	-6684.00	0.00	0.00	0.00
86	4350.00	6270.00	-6684.00	0.00	0.00	0.00
87	4350.00	6460.00	-6684.00	0.00	0.00	0.00
88	4405.00	6270.00	-6710.00	0.00	0.00	0.00
89	4405.00	6450.00	-6710.00	0.00	0.00	0.00
90	4435.00	6270.00	-6710.00	0.00	0.00	0.00
91	4435.00	6450.00	-6710.00	0.00	0.00	0.00
92	4480.00	6280.00	-6710.00	0.00	0.00	0.00
93	4480.00	6490.00	-6710.00	0.00	0.00	0.00
94	4600.00	6280.00	-6710.00	0.00	0.00	0.00
95	4600.00	6450.00	-6710.00	0.00	0.00	0.00
96	4405.00	6500.00	-6570.00	0.00	0.00	0.00
97	4435.00	6500.00	-6570.00	0.00	0.00	0.00
98	4405.00	6500.00	-6710.00	0.00	0.00	0.00
99	4435.00	6500.00	-6710.00	0.00	0.00	0.00
100	4430.00	6500.00	-6710.00	0.00	0.00	0.00
6800						
101	4070.00	6400.00	-6796.00	0.00	0.00	0.00
102	4180.00	6230.00	-6796.00	0.00	0.00	0.00
103	4160.00	6300.00	-6796.00	0.00	0.00	0.00
104	4180.00	6460.00	-6796.00	0.00	0.00	0.00
105	4350.00	6230.00	-6796.00	0.00	0.00	0.00
106	4350.00	6270.00	-6796.00	0.00	0.00	0.00
107	4350.00	6460.00	-6796.00	0.00	0.00	0.00
108	4405.00	6270.00	-6796.00	0.00	0.00	0.00
109	4405.00	6450.00	-6796.00	0.00	0.00	0.00
110	4430.00	6270.00	-6796.00	0.00	0.00	0.00
111	4430.00	6450.00	-6796.00	0.00	0.00	0.00
112	4480.00	6280.00	-6796.00	0.00	0.00	0.00
113	4480.00	6450.00	-6796.00	0.00	0.00	0.00
114	4600.00	6310.00	-6796.00	0.00	0.00	0.00
115	4600.00	6450.00	-6796.00	0.00	0.00	0.00
116	4600.00	6305.00	-6710.00	0.00	0.00	0.00
117	4600.00	6345.00	-6710.00	0.00	0.00	0.00
118	4600.00	6332.00	-6796.00	0.00	0.00	0.00
119	4600.00	6357.00	-6796.00	0.00	0.00	0.00
120	4660.00	6320.00	-6708.00	0.00	0.00	0.00
6900						
121	4320.00	6300.00	-6906.00	0.00	0.00	0.00
122	4320.00	6420.00	-6906.00	0.00	0.00	0.00
123	4430.00	6240.00	-6906.00	0.00	0.00	0.00
124	4430.00	6510.00	-6906.00	0.00	0.00	0.00
125	4520.00	6240.00	-6906.00	0.00	0.00	0.00
126	4520.00	6510.00	-6906.00	0.00	0.00	0.00

127	4660.00	6330.00	-6906.00	0.00	0.00	0.00
128	4660.00	6500.00	-6906.00	0.00	0.00	0.00
129	4770.00	6340.00	-6906.00	0.00	0.00	0.00
130	4770.00	6460.00	-6906.00	0.00	0.00	0.00
* 7000						
131	4320.00	6300.00	-7008.00	0.00	0.00	0.00
132	4320.00	6420.00	-7008.00	0.00	0.00	0.00
133	4430.00	6240.00	-7008.00	0.00	0.00	0.00
134	4430.00	6510.00	-7008.00	0.00	0.00	0.00
135	4520.00	6240.00	-7008.00	0.00	0.00	0.00
136	4520.00	6510.00	-7008.00	0.00	0.00	0.00
137	4660.00	6330.00	-7008.00	0.00	0.00	0.00
138	4660.00	6500.00	-7008.00	0.00	0.00	0.00
139	4770.00	6340.00	-7008.00	0.00	0.00	0.00
140	4770.00	6460.00	-7008.00	0.00	0.00	0.00
* grid 1						
141	4400.00	6450.00	-6750.00	0.00	0.00	0.00
142	4400.00	6450.00	-6550.00	0.00	0.00	0.00
143	4800.00	6450.00	-6550.00	0.00	0.00	0.00
144	4800.00	6450.00	-6750.00	0.00	0.00	0.00
*						
145	4400.00	6000.00	-6570.00	0.00	0.00	0.00
146	4400.00	6600.00	-6570.00	0.00	0.00	0.00
147	4800.00	6600.00	-6570.00	0.00	0.00	0.00
148	4800.00	6000.00	-6570.00	0.00	0.00	0.00
*						
151	4400.00	6000.00	-6640.00	0.00	0.00	0.00
152	4400.00	6600.00	-6640.00	0.00	0.00	0.00
153	4800.00	6600.00	-6640.00	0.00	0.00	0.00
154	4800.00	6000.00	-6640.00	0.00	0.00	0.00
*						
155	4400.00	6390.00	-6750.00	0.00	0.00	0.00
156	4400.00	6390.00	-6550.00	0.00	0.00	0.00
157	4800.00	6390.00	-6550.00	0.00	0.00	0.00
158	4800.00	6390.00	-6750.00	0.00	0.00	0.00
* slot 6600						
159	4405.00	6270.00	-6570.00	0.00	0.00	0.00
160	4430.00	6270.00	-6570.00	0.00	0.00	0.00
* 1290 vrm						
161	4660.00	6345.00	-6708.00	0.00	0.00	0.00
162	4660.00	6335.00	-6800.00	0.00	0.00	0.00
163	4660.00	6355.00	-6800.00	0.00	0.00	0.00
* coords to define top west cornor of 4300 ext hor 6900lev.						
* 164	4160.00	6300.00	-6655.00	0.00	0.00	0.00
* 165	4180.00	6490.00	-6655.00	0.00	0.00	0.00
* 4460 vrm 66-6700						
166	4435.00	6435.00	-6710.00	0.00	0.00	0.00
167	4480.00	6435.00	-6710.00	0.00	0.00	0.00
168	4435.00	6435.00	-6570.00	0.00	0.00	0.00
169	4480.00	6435.00	-6570.00	0.00	0.00	0.00
170	4480.00	6480.00	-6570.00	0.00	0.00	0.00
171	4480.00	6480.00	-6710.00	0.00	0.00	0.00
172	4435.00	6480.00	-6710.00	0.00	0.00	0.00
173	4435.00	6480.00	-6570.00	0.00	0.00	0.00

joiners and ext hor 4300 70000

174	4430.00	6450.00	-6906.00	0.00	0.00	0.00
175	4320.00	6450.00	-6906.00	0.00	0.00	0.00
176	4324.00	6276.00	-6906.00	0.00	0.00	0.00
177	4430.00	6220.00	-6895.00	0.00	0.00	0.00
178	4430.00	6405.00	-6895.00	0.00	0.00	0.00
179	4430.00	6450.00	-6895.00	0.00	0.00	0.00
180	4320.00	6450.00	-6895.00	0.00	0.00	0.00
181	4324.00	6276.00	-6895.00	0.00	0.00	0.00

0/

Initial Field Stresses
Material number 1 is reserved for the far field stresses
T x-y (dip direction) and T z-xy (dip) refer to the orientation of S1
T x-y is measured counterclockwise from the X-axis towards the Y-axis
T z-xy is measured from the X-Y plane down towards the negative Z-axis
Use a zero material number to end the list

Matl	Principal Stresses						Orientation	
#	S1 = a * z + b		S2 = a * z + b		S3 = a * z + b		T x-y	T z-xy
1	-1.80	1575.00	-1.29	0.00	-1.29	0.00	0.00	0.00

0/

Material properties list
Material number 1 is reserved for the host rock
Use a zero material number to end the list
Shear Modulus, G = E / (2(1 + v))
Strength Parameter, phi is in degrees
Element type 1 or 3: Massive Materials
0 No failure: Elastic only
(-) Failure: Plastic only
(+/-)1 Mohr/Coulomb: Sig:1 = Co + 2So tan(45 + phi/2) + Sig:3 tan(45 + phi/2)**2
(+/-)2 Hoek/Brown: Sig:1 = Sig:3 + (m Co Sig:3 + s Co**2)**(1/2)
Element type 2: Tabular materials with closure restriction
(+/-)3 Uniaxial: Sig:N = Co
Mohr/Coulomb: Sig:S = So + Sig:N tan(phi)
(+/-)4 Salamon/Munro: Sig:N = Co Width**0.46 / Height**0.66
Mohr/Coulomb: Sig:S = So + Sig:N tan(phi)
Pillar widths are determined for adjacent elements with the same material type

Material		Peak Strength / Residual Strength					
Number	Type	Young's Modulus	Poisson's Ratio	To	Co	So/s	phi/s
1	1	1.00E+07	0.30	0.00	9000.00	0.00	35.00
		1.00E+07	0.30	0.00	9000.00	0.00	35.00

0/

Grid Point List
Use a zero grid number to end the list

Grid #	Coordinate Number Incidences								# Div Between		
	1	2	3	4	5	6	7	8	1-2	2-3	1-5
1	141	142	143	144	141	142	143	144	25	25	0
2	145	146	147	148	145	146	147	148	25	25	0
3	151	152	153	154	151	152	153	154	25	25	0
4	155	156	157	158	155	156	157	158	25	25	0

0/

Mining Step 1
Boundary Condition List
Element number = (+) to specify entire blocks
= 0 to end the list
= (-) to specify individual elements
Use zero element number to end the list
Code = 1 to specify: Value = stress
= 2 to specify: Value = displacement
= 3 to specify: Value = SD, DD, or SO
= (-) to specify: Code = number of new material inserted
Value = initial placement stress in addition to the field stress associated with the material (note: plastic def'm is initialized to zero)
Initial default is code 3, with value = zero, and stress = field stress

Elem #	Code	Value XX	YY	ZZ/H	XY	YZ/S23	ZX/S12
6000-6200							
1	1	0.00	0.00	1000.00	0.00	0.00	0.00
2	1	0.00	0.00	1000.00	0.00	0.00	0.00
3	1	0.00	0.00	1000.00	0.00	0.00	0.00
4	1	0.00	0.00	1000.00	0.00	0.00	0.00
5	1	0.00	0.00	1000.00	0.00	0.00	0.00
6	1	0.00	0.00	1000.00	0.00	0.00	0.00
7	1	0.00	0.00	1000.00	0.00	0.00	0.00
8	1	0.00	0.00	1000.00	0.00	0.00	0.00
9	1	0.00	0.00	1000.00	0.00	0.00	0.00
6200-6400							
10	1	0.00	0.00	1000.00	0.00	0.00	0.00
11	1	0.00	0.00	1000.00	0.00	0.00	0.00
12	1	0.00	0.00	1000.00	0.00	0.00	0.00
13	1	0.00	0.00	1000.00	0.00	0.00	0.00
14	1	0.00	0.00	1000.00	0.00	0.00	0.00
15	1	0.00	0.00	1000.00	0.00	0.00	0.00
16	1	0.00	0.00	1000.00	0.00	0.00	0.00
17	1	0.00	0.00	1000.00	0.00	0.00	0.00
18	1	0.00	0.00	1000.00	0.00	0.00	0.00
6400-6600							
19	1	0.00	0.00	1000.00	0.00	0.00	0.00
20	1	0.00	0.00	1000.00	0.00	0.00	0.00
21	1	0.00	0.00	1000.00	0.00	0.00	0.00
22	1	0.00	0.00	1000.00	0.00	0.00	0.00
23	1	0.00	0.00	1000.00	0.00	0.00	0.00
24	1	0.00	0.00	1000.00	0.00	0.00	0.00

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    25     1        0.00        0.00     1000.00        0.00        0.00        0.00
    26     1        0.00        0.00     1000.00        0.00        0.00        0.00
    27     1        0.00        0.00     1000.00        0.00        0.00        0.00
* 6700-6800
    28     1        0.00        0.00     1000.00        0.00        0.00        0.00
    29     1        0.00        0.00     1000.00        0.00        0.00        0.00
    30     1        0.00        0.00     1000.00        0.00        0.00        0.00
    31     1        0.00        0.00     1000.00        0.00        0.00        0.00
    32     1        0.00        0.00     1000.00        0.00        0.00        0.00
    33     1        0.00        0.00     1000.00        0.00        0.00        0.00
    34     1        0.00        0.00     1000.00        0.00        0.00        0.00
* 6900-7000
    35     1        0.00        0.00     1000.00        0.00        0.00        0.00
    36     1        0.00        0.00     1000.00        0.00        0.00        0.00
    37     1        0.00        0.00     1000.00        0.00        0.00        0.00
    38     1        0.00        0.00     1000.00        0.00        0.00        0.00
* slot
    39     1        0.00        0.00     1000.00        0.00        0.00        0.00
    40     1        0.00        0.00        0.00        0.00        0.00        0.00
    41     1        0.00        0.00        0.00        0.00        0.00        0.00
    42     1        0.00        0.00        0.00        0.00        0.00        0.00
    43     1        0.00        0.00     1000.00        0.00        0.00        0.00
    44     1        0.00        0.00        0.00        0.00        0.00        0.00
    45     1        0.00        0.00     1000.00        0.00        0.00        0.00
    46     1        0.00        0.00        0.00        0.00        0.00        0.00
     0/
* ------------------------------------------------------------------------------
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